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by Joseph P. Seney
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EROSIONAL IMPACT OF HIKERS, HORSES, OFF-ROAD BICYCLES, AND MOTORCYCLES ON MOUNTAIN TRAILS

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ABSTRACT

Little is known about the erosional impacts of hikers, horses, motorcycles and off-road bicycles on mountain trails. The purpose of this investigation was to determine the relative impacts of different trail uses with respect to water runoff and sediment yield. A total of 108 sample plots were examined on existing trails in or near the Gallatin National Forest of southwestern Montana. A modified Meeuwig drip-type rainfall simulator was used to reproduce natural rainstorm events. Treatments of 100 passes were applied to each of the sample plots. This approach meant that 24 sample plots were established for each treatment type (hiking, horseback riding, motorcycling, bicycling) in addition to 12 sample plots for the control or null hypothesis case to represent two soil texture groupings (clay and sandy clay or loam and sandy loam), two antecedent soil moisture classes (dry and prewetted), and two slope gradients (0-6 percent and 8-21 percent), and three replications.

The results of this study demonstrate the interaction of topographic, soil, and geomorphic variables and the difficulty of understanding natural processes on existing trails. None of the hypothesized relationships between water runoff and slope, soil texture, antecedent soil moisture, trail roughness, and soil resistance were statistically significant. However, the multiple regression results for sediment yield were statistically significant. Five independent variables or cross-products explained 42% of the variability in sediment yield when soil texture was used as a series of indicator variables. The addition of a trail user as a second series of indicator variables explained an additional 28% of the variability in sediment yield. Ten variables combined to explain 70% of the variability in sediment yield with simple or combined variables incorporating soil texture (37%), slope (35%), user treatment (35%), and accounting for the largest contributions. The use of multiple comparison tests clarify the roles of the different trail users and in particular showed that horses and hikers (hooves and feet) made more sediment available than wheels (motorcycles and off-road bicycles). This effect was most pronounced on prewetted trails.

INTRODUCTION

1.1 Scope and Purpose

The tremendous increase in outdoor recreation during the past two decades has created crowded conditions and intensified environmental impact in nature reserves, national forests and parks, and state and municipal recreation centers (McQuaid-Cook, 1978; Cole, 1989). A 1975 survey of land managers reported substantial erosion on mountain trails during the previous decade (Godin and Leonard, 1979). The erosion was attributed to dramatic increases in horse and foot travel on trails not designed to accommodate higher volumes of traffic. The National Park Service (1975) predicted that soil compaction and erosion caused by foot and horse traffic on trails would contribute the most environmental damage to trail systems in the future; however, trail use during the past ten years has grown to include off-road bicycles and motorcycles as well as horse and foot traffic. Off-road bicyclists in many cases use the same trails as hikers, horses and motorcycles, so that this additional use compounds erosional concerns and user conflicts. Intensive use of recreation areas may cause irreversible damage to trails in a short period of time as increased use reduces plant growth, destroys ground cover, and increases runoff and soil erosion (Dotzenko et al., 1967).

Today's land managers need to assess the carrying capacities of their trail systems as they struggle to accommodate the increased numbers of users and still maintain high quality recreational experiences. The increased use and popularity of off-road bicycles during the past ten years has increased user conflicts and erosional concerns among land managers and environmental organizations (Douglas, Shovic, pers. comm., 1989). The development of pertinent studies to assess trail user impacts and conflicts will help land managers develop policies to regulate off-road bicycling and other trail uses. The results of studies comparing different trail users will allow land managers to evaluate the trail impacts of all users and differentiate the emotional and environmental arguments that are presently invoked to support and/or challenge one or more of these uses.

This study assesses the erosional impacts of hikers, horses, motorcycles, and off-road bicycles on two existing mountain trails. The study had three objectives as follows: 1) quantify the individual and combined relationships between water runoff and selected topographic and soil variables; 2) quantify the individual and combined relationships between sediment yield and selected hydrologic, topographic, and soil variables; and 3) quantify the relative impacts of different trail uses on water runoff and sediment yield.

1.2 Quantifying Trail Impacts

The durability of recreational sites is influenced by the physical and human site characteristics. Climate, terrain attributes, and soil properties determine the physical site characteristics. The critical human site characteristics are more complicated. For example, the type and volume of use reflect the distance of the recreational site from population centers and the perceived intrinsic qualities of the site, so that sites adjacent to large population centers often experience greater levels of use. Heavy use often leads to increased user conflicts, erosional concerns, and a decrease in the perceived intrinsic qualities of recreational sites. The ability of recreational sites to tolerate recreational use is partially dependent on intensity and type of use. When the intensity of use exceeds some threshold value related to some perceived or actual human or physical site characteristic, land managers may limit the types and quantity of use or they may alter and repair recreational sites to better withstand higher intensities of use. For example, a few trails located in Yosemite National Park, California have been paved or graveled to reduce trail erosion caused by heavy use.

The choice and location of recreational sites, site construction methods, and types and intensities of use affect the quality and durability of these sites. Trail systems are necessary to provide access to recreational sites; however, the quality of a recreational experience is inevitably reduced as trail use and trail degradation increase. Past trail studies have focused on foot, horse, and motorcycle traffic. Most studies have examined the relationship between trail location, methods of trail construction, and type and frequency of use with vegetation and/or soil impacts (e.g., Bates, 1935; Dotzenko et al., 1967; Ketchledge and Leonard, 1970; Dawson et al., 1974; Helgath, 1975; Bryan, 1977; Weaver and Dale, 1978; Bratton et al., 1979; Leonard and Plumley, 1978; Summer, 1980, 1986; Coleman, 1981; Fish et al., 1981; Kuss and Morgan, 1980; Jubenville and O'Sullivan, 1987; Kuss, 1987). Other studies have attempted to model recreation-induced soil erosion effects or the physical carrying capacity of natural areas by utilizing the Universal Soil Loss Equation (e.g., Kuss and Morgan, 1980, 1984).

Alteration of the biotic environment due to trampling and subsequent trail development can be related to the resilience of an ecosystem and its carrying capacity. Burden and Randerson (1972) define carrying capacity as "the maximum intensity of use an area will continue to support under a particular management regime without inducing a permanent change in the biotic environment". Carrying capacity is a function of the physical and biological factors that influence the erosion potential of recreation sites (Kuss and Morgan, 1984).

The pressure exerted per unit area of ground per unit time integrates the effect of weight, size of impact area, length of impact and frequency of use, and may indicate recreational user impacts and rates of trail degradation (Burden and Randerson, 1972). However, information about location of frequency use is seldom available and many researchers have resorted to physical and biological variables to estimate carrying capacity and recreational impacts.

Klock and McColley (1978), for example, suggested four site factors that determine the durability of recreational sites: trafficability, depth, drainage, and erodibility. Trafficability was defined as the capacity of a soil to bear a moving load. This factor is highly dependent on the strength of the soil which, in turn, is influenced by the texture, structure, and permeability. Soil resistance also varies with soil moisture levels through time (Lull, 1959). Travel over wet soils often increases compaction and, in turn, reduces porosity, particularly the volume of macropores (Cole, 1987). This tends to reduce water-holding capacity in fine-textured soils and increase it in coarse-textured soils. Coarse-textured soils (i.e., coarse sands) tend to resist erosion because the particles are not easily detached or moved; however, the soils are structurally unstable and trail width is easily increased. In contrast, fine-textured soils (i.e., silt and clays) are highly erodible and easy to detach and move (Cole, 1987).

Depth was defined by Klock and McColley (1978) as the amount of unconsolidated soil material above bedrock. This factor is related to the durability of recreational sites because it affects the moisture and nutrient pools available for plant growth. Hence, shallow soils are more sensitive to vegetation disturbance and more susceptible to erosion and/or trail widening once the soil is exposed.

Drainage was defined by Klock and McColley (1978) as the propensity of the soil within an area to retain groundwater. This factor is related to the durability of recreational sites because the vegetation species found in poorly drained areas usually suffer more from disturbance than the vegetation species found in well-drained areas. Trails located on poorly drained soils are usually deeper and display greater roughness than trails located on well-drained sites (Weaver and Dale, 1978).

Erodibility was defined by Klock and McColley (1978) as the resistance of a soil to displacement by the action of wind or water. Highly erodible soils are less likely to withstand a given level of use and therefore are less durable than less erodible soils. Generally, soils with good aggregation and intermediate texture (sandy loams to loams) appear to be least erosive while silty-clay, clay, or fine-textured soils are most susceptible to wind and water erosion (Meeuwig, 1971b; Klock and McColley, 1978; Leonard and Plumley, 1978). However, other factors affect rates of wind and/or water erosion as well. Farmer and Van Haveren (1971), for example, showed that 90 percent of the variability in soil erosion was due to variations in rainfall intensity and slope gradient in their study of mountain soils in Utah and Idaho. Slope gradient and soil loss are positively correlated (Wischmeier and Smith, 1978) and steeper slopes often experience increased trail degradation (Leonard and Plumley, 1978).

Many studies have examined the impacts of foot, horse, and motorcycle recreation uses on vegetation along trails without examining the carrying capacity of recreational trails (Bates, 1935; Bayfield, 1971; Chappell et al., 1971; Burden and Randerson, 1972; Liddle and Moore, 1973; Dale and Weaver, 1974; Liddle, 1975; Liddle and Greig-Smith, 1975; Cole, 1978; Weaver and Dale, 1978; Summer, 1980). Removal of vegetation can increase direct precipitation and solar intensity along trails which, in turn, alters trailside microclimate and plant composition (Cole, 1978). Trampling or removal of vegetation is generally the first consequence of planned and unplanned trail formation (Quinn and Morgan, 1980).

By the time vegetation wear is noticed the critical period in which accelerated erosion occurs has already passed (Quinn and Morgan, 1980). Water runoff is expected to increase in the early stages of trampling because infiltration is decreased due to increased density (compaction) of the soil (Quinn and Morgan, 1980; Cole, 1987; Kuss, 1987). Most studies show that trampling increases the bulk density of the soil which, in turn, changes soil porosity, moisture content, aeration, and the availability of soil nutrients (Baver, 1933; Liddle and Greig-Smith, 1975; Weaver and Dale, 1978; Kuss, 1983).

Once vegetation is removed erosion is the primary problem, especially where trails channel water which is not diverted from the tread (Cole, 1987). Trails located parallel to the slope channel water down the trail and increase erosion when compared to trails oriented perpendicular to the slope (Bratton, et al, 1979). Potential erosion is influenced by the position of the trail with respect to the top or bottom of a slope in addition to the gradient of the slope along and across the trail. Summer (1986), for example, examined trails in Rocky Mountain National Park in northcentral Colorado and suggested trails located below the crest of a hillslope will erode at a higher rate than trails located on other segments of the slope. The erosion potential increases exponentially as the slope gradient exceeds 12 to 13 percent (Coleman, 1981). Slope gradient is closely associated with type of landform (Helgath, 1975). Bratton et al. (1979), for example, inventoried trail degradation in Great Smokey Mountain National Park of eastern Tennessee and western North Carolina, and found that the slope of the trail was the most important factor in explaining rates of trail deterioration.

The results from other studies indicate that soil factors also influence trail degradation. Bryan (1977), for example, examined mountain hiking trails in Grovelsjon, Sweden and related the severity of degradation to soil resistance. Soil resistance was estimated from several soil properties, including aggregate stability, soil texture, and quantity of coarse fragments embedded in or on the trail. He thought that particle aggregation initially increases up to a threshold determined by the soil shearing strength when pressure is exerted on soil. Aggregation declined and soil erodibility and soil loss increased once this threshold was reached. The loose materials in or on the trail tend to counteract soil compaction and increase resistance during the early stages of trail degradation. However, coarse fragments promote erosion by increasing the turbulence and erosive capacity of trail runoff when trail use continues because loose materials saltate along the trail corrading the trail bed and undermining trail sides (Bryan, 1977).

In contrast to the previous group of studies which focused on natural processes and controls, a smaller group (Ketchledge and Leonard, 1970; Dale and Weaver, 1974; Helgath, 1975; Weaver and Dale, 1978; Bratton, 1979; Burde and Renfro, 1986) has examined the relationships between topographic and soil variables and the impacts of foot, horse, and motorcycle traffic on trails. These studies show that different trail uses result in different trail erosion rates, probably because different users exert different impacts per unit area (Lull, 1959). The impact per unit area combines the weight of the user and size of the impact area or "foot print" of the user. Weaver and Dale (1978), for example, found that horse use caused more pronounced increases in trail width, depth, litter, and soil compaction than hiking and motorcycling. Horse traffic applies the greatest impact (force) per unit area among hikers, horseback riders, off-road bicyclists, and motorcyclists.

Weaver and Dale (1978) also compared motorcycle erosion with horse and foot erosion and found that motorcycles moving uphill established a narrow rut which served as a funnel and increased the velocity and sediment transport capacity of trail runoff. The development of a linear channel was the direct result of the imprint of the tire and the torque applied by the motorcyclist which, in turn, led to increased erosion. However, motorcycles moving downhill, when torque is not needed, did not greatly affect the rate of trail degradation. In contrast to motorcyclists, hikers and horses do not rely on the same forces to decelerate. Hikers and horses tend to loosen soil when descending a steep trail; hence, greater forces were applied when decelerating and moving down a steep trail. Shear stresses are increased and compressional stresses are reduced on steeper slopes which increases the quantities of loose sediment available for transport (Quinn and Morgan, 1980). Weaver and Dale (1978) suggested motorcycles ascend gentle slopes and descend steep slopes and hikers and horses ascend steep slopes and descend gentle slopes to minimize erosional impacts.

The studies referred to above have important implications for this project, even though they do not examine erosion from off-road bicycles nor refer to existing trails in many cases. In particular, they demonstrate the importance of rainfall intensity and slope gradient as key factors in explaining variation in sediment yield. Soil properties, such as structure, texture, and moisture content determine the resistance to erosion and play secondary roles. The variety of results from past studies exemplify the difficulty of understanding the natural variability of trail degradation. Several studies show trail degradation occurs regardless of specific uses and is more dependent on the geomorphic processes that occur in different landscapes; however, most studies to date have focused on one particular trail use.

The approach of this study was different because an attempt was made to superimpose human impacts on the "natural" factors that influence trail erosion. This approach was needed to evaluate the relative impacts of different trail uses. Few other studies reported in the literature to date have attempted this type of analysis.

1.3 Description of Study Area

Two existing trails near Bozeman, Montana were selected as study sites for this project because of ease of access, availability of water from adjacent streams, long consistent sections of trail, and a diversity of slope gradients and soil textures. Both trails, the Emerald Lake trail located 39 km south and the New World Gulch trail located 12 km southeast of Bozeman, Montana (population approximately 30,000) are easily accessible and have experienced all four types of use (foot, horse, motorcycle and off-road bicycle traffic) over the past ten years (Figure 1).

Both study sites were located in or near the Gallatin National Forest, Montana (45°30'N, 111°W) which borders the northern and western boundaries of Yellowstone National Park. The topography within this forest ranges from forested foothills to rugged rocky alpine peaks. The forests consist mainly of lodgepole pine (Pinus contorta) and Douglas fir (Pseudotsuga menziesii), with a variety of other species occupying smaller and more specific niches. Approximately 500 km of trails provide recreational opportunities for the four user groups examined in this project. The characteristics of both trails are summarized in Table 1.

The Emerald Lake trail study site was located within the Gallatin National Forest and consisted of a 1.6 km section of trail at an approximate elevation of 2000 m. The land surface consists of hummocky, rolling glacial till deposits. The morainal deposits at this study site occupy the bottom of a U-shaped valley. The parent material consists of glacial till deposits of Pleistocene age and are primarily derived from layered, volcanic rock (Davis and Shovic, 1984). These medium-textured deposits contain variable amounts of subrounded rock fragments.

Soils are generally well-drained with medium to moderate textures. Subsoil clay accumulation occurs in some locations. Rock fragments in the lower soil horizons range from 35-50 percent. The soils within the study site are classified as mixed, loamy skeletal, Typic Cryoboralfs (Davis and Shovic, 1984). A dense lodgepole pine (Pinus contorta) forest surrounds this study site. The understory is composed of a thick groundcover of grouse whortleberry (Vaccinium scoparium), dwarf huckleberry (Vaccinium caespitosum), and twinflower (Linnaea borealis). The annual precipitation in this area is 65-90 cm and 60 percent falls as

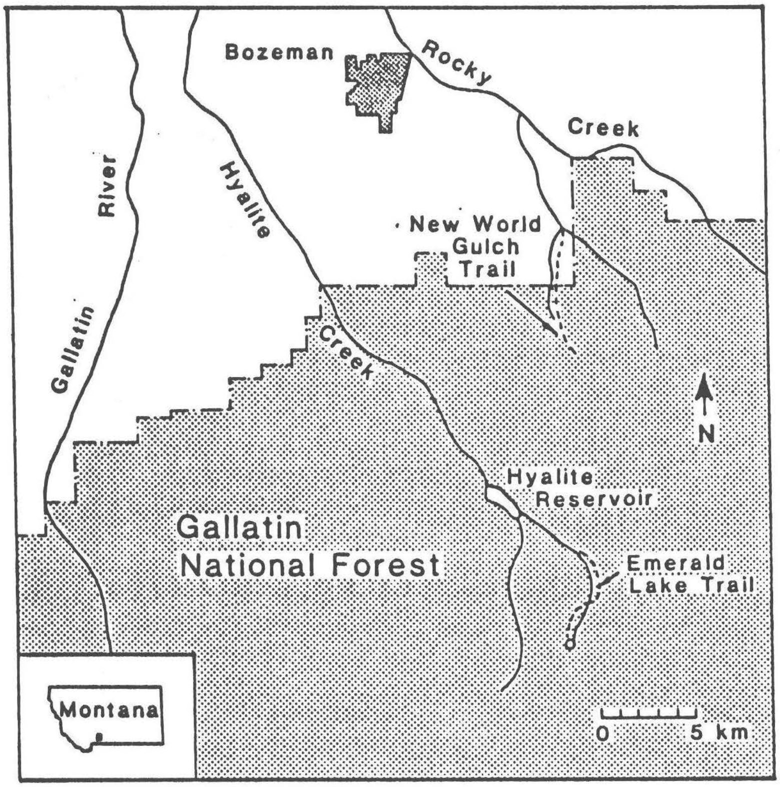

Figure 1. Location of Emerald Lake and New World Gulch trails.

snow. Trail accessibility in April and May is limited by the remaining snowpack and saturated surface soils. Peak runoff from the nearby stream usually occurs in late April and early May (Davis and Shovic, 1984).

The New World Gulch trail study site was located on land immediately outside the Gallatin National Forest administered by the State of Montana and consisted of a 0.8 km section of trail at an approximate elevation of 1600 meters. The topography consists of ridges with steep slopes and occasional small valleys or swales (Davis and Shovic, 1984). The locations of ridges and swales are controlled by the underlying bedrock, with the more resistant sandstones and limestones forming ridges and shales and siltstones forming swales and valleys. The bedrock of this area consists of Lower Cretaceous Mowry and Thermopolis shale, Kootenai Formation sandstone and mudstone, and Jurassic Morrison Formation shale, siltstone and mudstone (Roberts, 1964).

Fine- and medium-textured soils have formed in material weathered from thickly bedded sandstones and shales. The soils are classified as mixed, fine loamy Typic Cryoboralfs (Davis and Shovic, 1984). Overall, soils in this area are moderately well-drained with fine and medium textures. Vegetation surrounding this trail consists predominantly of perennial grasses and some Douglas-fir (Pseudotsuga menziesii). The annual precipitation is similar to the first trail (65-90 cm with 60 percent falling as snow). Trail accessibility between April-May and October-November is

Table 1. Study site characteristics.

Characteristics	Emerald Lake Trail	New World Gulch Trail
Parent material	Glacial till	Sandstone, shale
Soil texture	Sandy loam, loam	Clay, sandy clay
Elevation	2000 m	1600 m
Slope (on trail)	3-17%	2-21%
Aspect	Northeast	North
Vegetation	Lodgepole pine	Grasses, Douglas-fir

restricted due to saturation of the predominantly clayey soils.

METHODS

The first two objectives of this research were concerned with the natural variability and geomorphic controls operating on the sections of trails used in the study. The relationships between water runoff and sediment yield, and selected hydrologic, topographic, and soil variables were examined. The third and final objective sought to superimpose human impacts on these geomorphic controls in an attempt to evaluate the relative impacts of different trail uses. This chapter describes the methods used for data collection and analysis.

2.1 Study Design and Site Selection

A modified Meeuwig drip-type rainfall simulator was used to reproduce natural rainstorm events and treatments of 100 passes were applied to a total of 108 sample plots on the Emerald Lake and New World Gulch trails. There were 54 sample plots on each of the Emerald Lake and New World Gulch trails consisting of 12 sample plots for each mode of travel (hiking, off-road bicycling, horseback riding, and motorcycling treatment plots) and six sample plots for the control or null treatment case. The twelve sample plots for each mode of travel represented two antecedent soil moisture classes (dry and pre-wetted), two slope gradient classes

(0-6 and 8-21 percent), and three replications for each plot type. The control or null treatment plots combined the two antecedent soil moisture regimes, requiring only six plots.

Sample plot size (66 by 66 cm) was determined by the size of the containment tray that came with the rainfall simulator. Locations of sample plots were determined on reconnaissance hikes along the Emerald Lake and New World Gulch trails in the spring of 1989. Trail sections with uniform slope and soil conditions were selected for study plots, avoiding sections of trail with protruding rocks or roots. Where necessary litter and large loose stones were removed from the sample plots before treatments.

2.2 Soil Description and Classification

Soil pits were dug adjacent to each trail segment and the Keys to Soil Taxonomy (Soil Survey Staff, 1988) were used to describe and classify the soils. A total of four shallow pits were dug across sections of trail to compare soils on and off the trail.

2.3 Field Experiments and Measurements

User treatments were assigned to sample plots based on the availability of the user (hikers, horses, motorcycle and rider, mountain bike and rider), antecedent soil moisture, slope gradient class needed for the particular user (0-6 or 8-21 percent), and daily weather. Afternoon thundershowers reduced the number of experiments conducted on certain days. Four plots were examined on most field days, although six plots were examined on days with good weather and dry treatments.

Data collection consisted of the seven tasks summarized in Table 2. Slope gradient, trail roughness, and soil resistance were measured prior to treatment for each sample plot during Task 1. Slope gradient was measured with a Brunton compass and 3 by 0.6 m board. The 3 m board was placed on the trail and several slope measurements were taken with the Brunton compass on the board to determine the slope gradient along specific sections of trail. Trail roughness or micro-relief was measured using 12 transects marked off at 2.54 cm intervals along each sample plot and a 91.5 cm long, 5 by 10 cm board with 13 evenly spaced slots. A metal ruler was then inserted into each slot moving left to right and a depth measurement was taken for each of the 13 slots (Figure 2). High values represented depressions and low values elevated spots on the trail.

Soil resistance was measured at selected points along transects with a Soiltest, Inc. CN-970 proving ring penetrometer. Hence, soil resistance was treated as a measure of the force required to penetrate to a depth of 2.54 cm. The proving ring penetrometer is a cone type penetrometer which measures the

Table 2. Schedule of data collection activities.

Task	Summary of data collection activities
1	Collection of soil samples for soil texture and antecedent soil moisture measurements; slope, trail roughness and soil resistance measurements were taken.
	Skip tasks 2 and 3 for dry treatment plots.
2.	Meeuwig rainfall simulator was erected over the plot and a 20 minute rainstorm with an intensity of 127 mm hr^{-1} was applied.
3.	Water runoff and sediment yield were collected; soil samples were taken for subsequent soil moisture measurements; and trail roughness and soil resistance were measured (again).
	Conduct tasks 4 through 7 on all plots.
4.	Treatments were applied (i.e., 50 hiking, bicycling, horseback riding and motorcycling passes); trail roughness and soil resistance were measured (again).
5.	Treatments were applied (i.e., an additional 50 hiking, bicycling, horseback and motorcycling passes); trail roughness and soil resistance were measured (again).
6.	Meeuwig rainfall simulator was erected over the plot and a 20 minute rainstorm with an intensity of 127 mm h^{-1} was applied.
7.	Water runoff and sediment yield were collected; soil samples were taken for subsequent soil moisture measurements; and trail roughness and soil resistance were measured (again).

penetration resistance of soils. The instrument consists of a T-handle, 45.7 cm penetration rod, 0.91 m extension, proving ring of 113.4 kg capacity with a dial indicator, and removable cone point (Figure 3).

The cone point used in this study had a base area of 6.34 cm^2 and conical area of 24.69 cm^2. When the cone is forced into the ground, the proving ring is deformed in proportion to the force applied. This force is thought to represent the shearing resistance of the soil (Liddle and Moore, 1973). The cone penetration was limited to one-half of the area of the cone; hence, the range values on the indicator dial could have been

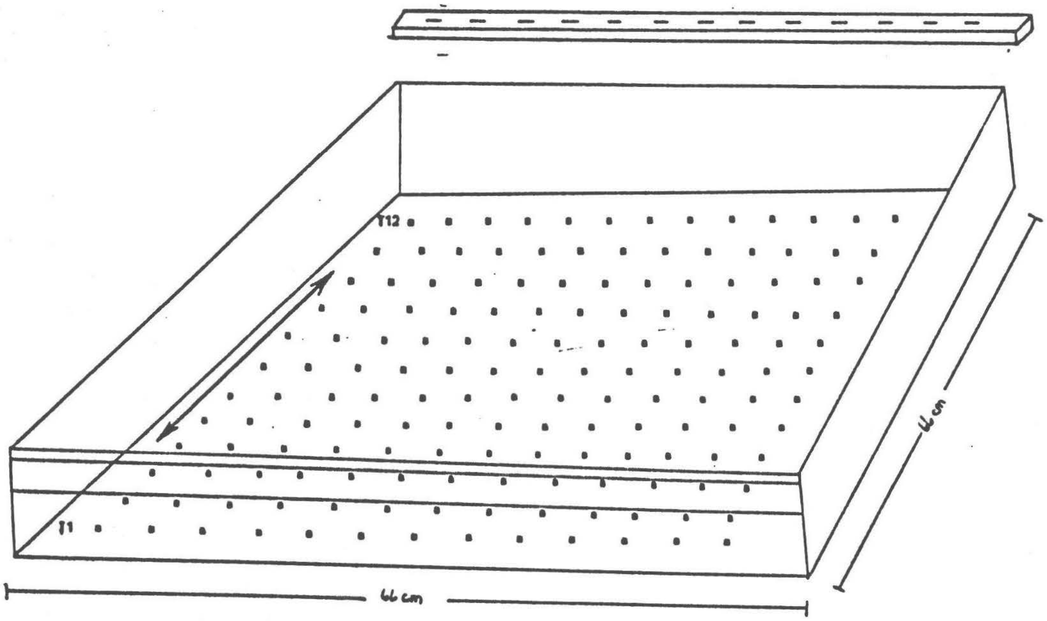

Figure 2. Systematic sample design and equipment used for trail roughness and soil resistance measurements.

doubled to reflect the smaller base area. These values were not doubled because they were only used for relative comparisons between types of trail use, so that the measurement scale was not of prime importance. Soil resistance values are expressed in kg of force per cm^2 throughout the thesis.

All 12 of the transects used for trail micro-relief measurements (Figure 2) were used for soil resistance measurements. A total of 11 soil resistance measurements were taken for each sample plot during tasks 1, 3, 4, 5, and 7. Hence, the transects labeled 1 and 7 were used during the first task, 2 and 8 for the third, 3 and 9 for the fourth, 4 and 10 for the fifth, and the fifth and eleventh transects were used for the seventh task (Figure 2). The designated transects were transferred to the next assigned task when a task was skipped (Table 2). The specific transects used to measure soil resistance were assigned in this manner to assure consistency from plot to plot.

Soil texture and moisture samples were taken during task 1. Soil moisture samples were also taken after the rainfall events that constituted the second and sixth tasks. These samples were collected in the field and stored in plastic containers in shady locations for transport back to Montana State University at the end of the field day. The second task consisted of no activity for dry treatments and a rainstorm if the treatment was to be applied to a prewetted plot. The rainfall simulator was erected over the plot and a 20 minute simulated rainstorm with a constant intensity of

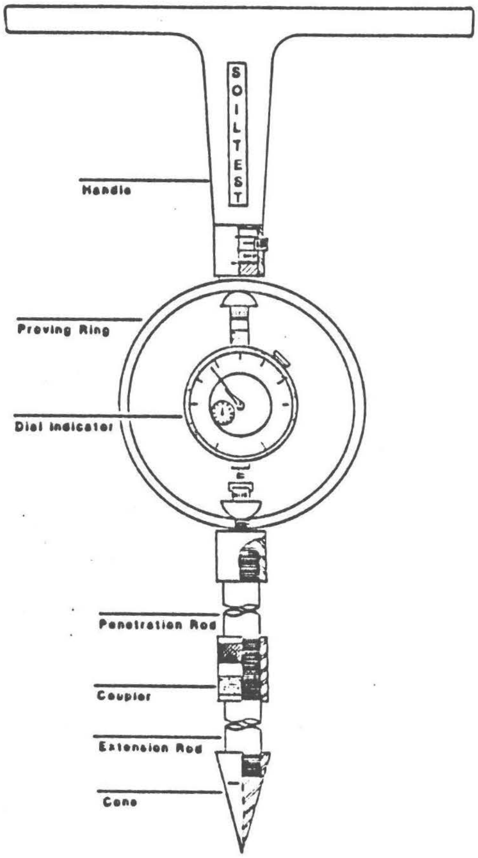

Figure 3. Sketch of CN-970 proving ring penetrometer (Modified from Soiltest, Inc. operations and service instructions diagram).

127 mm hr^{-1} was applied with a modified Meeuwig rainfall simulator (Schmid, 1988). This simulator was chosen because of its easy assembly and modest water requirements.

Field studies of erosion potential in mountainous terrain usually rely on natural rainfall events to provide the erosive force or rainfall needed for experiments. However, natural rainfall does not always provide the timing, location, and intensities needed for research. Simulated rainfall events provide rainstorms at desired times and places and, therefore, they allow the collection of large quantities of runoff and erosion data in relatively short periods of time.

The erosive energy of rainfall is usually expressed in terms of kinetic energy ($KE = 1/2MV^2$). The velocity (V^2) term in the equation reflects storm intensity. The intensity of a rainstorm varies with the distribution of raindrop sizes, since their size influences the velocity at which they fall (Law and Parsons, 1943). Drop velocity and terminal velocity are the same for natural rainstorm events, but the terminal velocities accompanying natural rainstorms are difficult to attain with portable rainfall simulators (Young, 1979).

The rainfall simulator used in this study was a modified Meeuwig drip-type simulator (Meeuwig, 1971a) with a drop fall height of 155 cm (Figure 4). The approximate waterdrop diameter at a simulated intensity of 127 mm per hour was 2.8 mm. The impact velocity for a 2.8 mm raindrop falling 155 cm is approximately 470 cm s^{-1} (Laws, 1941), whereas similar sized drops would achieve a terminal velocity of 780 cm s^{-1} in natural rainstorms (Gunn and Kinzer, 1949). Hence, the kinetic energy of simulated rainfall events in this study was roughly one-third that of a natural rainfall event.

The modified Meeuwig simulator used in the study had a 61 by 61 by 2.5 cm plexiglass water chamber with 500 drip needles made from hypodermic tubing. An electric motor was used to rotate the chamber to randomize the raindrops. A 18.9 l plastic container was elevated 20 cm above the water chamber to provide a continuous supply of water to the chamber, and a 20 minute rainstorm was applied at a constant intensity of 127 mm h^{-1}.

The third and seventh tasks listed in Table 2 required the collection of the surface runoff and sediment yield produced by the simulated rainstorms at the downslope end of each plot using a collection tray which funneled water and sediment into 0.76 l plastic containers. The containers were then emptied into larger 3.8 l containers for transportation back to the Montana State University Soils Laboratory for further analysis. Soil moisture samples were also taken and stored for future transport and analysis at the same times.

The application of the appropriate hiking, bicycling, horseback riding, and motorcycling treatments consisting of two sets of 50 passes so that soil resistance and trail roughness could be measured after 50 and 100 passes comprised Tasks 4 and 5. The horses and riders (Angela Nielsen and Wade Stoelting) were supplied by Dr. Gerald A. Nielsen of the Montana State University Department of Plant and Soil Science and the Honda XL125 motorcycle was supplied by the Bozeman District office of the Gallatin National Forest. Wade Stoelting was the mountain bike rider and Joseph Seney (author) was the hiker. Trail user treatments were applied with proper trail etiquette and within the speed limits of usual trail activity. User passes along the plots were at least 4 m in length, so that users could attain a natural trail gait.

2.4 Laboratory Procedures

Soil moisture, soil texture, water runoff, and sediment yield samples were analyzed at Montana State University's Soil Testing Laboratory. Wet soil moisture samples were weighed and then oven-dried for 24 hours at 110°C. Samples were then reweighed. Percent soil moisture was determined by moist soil weight minus dry soil weight divided by dry soil weight. The runoff samples were

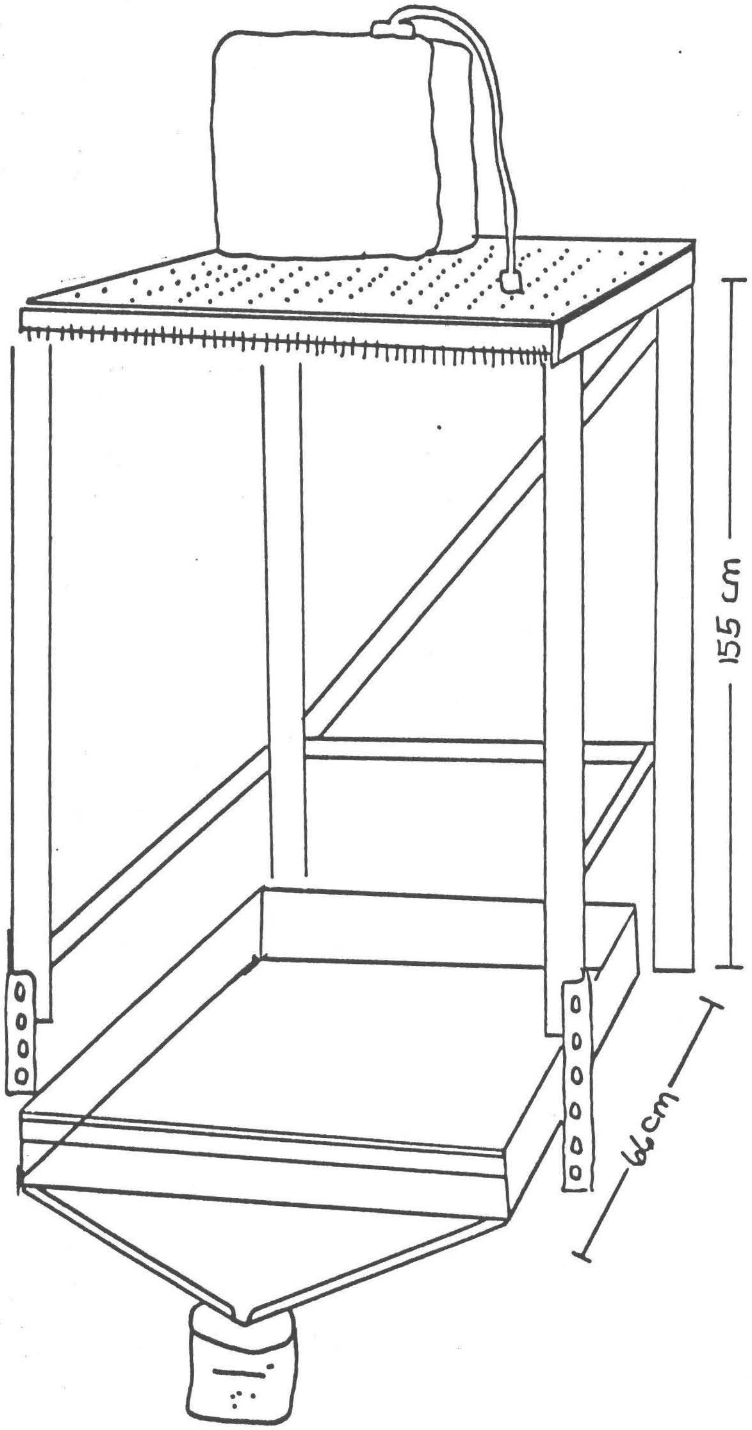

Figure 4. Sketch of Meeuwig rainfall simulator (from Schmid, 1988)

weighed using a Mettler PE 6000 ditigal scale water and placed in a soil drying room (18^0C) until all the water had evaporated from the containers. The remaining sediment and container were then reweighed. Twenty-five 3.8 l containers were weighed to determine the average weight of the containers, and this weight was then subtracted from the dry sediment and container weights to determine sediment and water runoff masses for each sample.

All 108 samples were hand textured using the "Feel" Method to determine a textural class (Thien, 1979). Twelve samples were then selected at random and mechanical analyze were performed by the Montana State University Soil Testing Laboratory staff. The Bouyoucos Mechanical Analysis technique was used to determine soil textural classes, and the results were compared with those obtained with the "feel" method. Eleven of the 12 "feel" method texture results were substantiated with the more elaborate technique (Table 3).

2.5 Statistical Methods

Three sets of statistical tests were used to assess the erosional impacts of trail users. First, bivariate regression models were used to represent simple relationships between the topographic and soil variables (i.e., independent variables) and water runoff and sediment yield (i.e., dependent variables). Multiple regression models were then developed to assess the cumulative relationships between these variables. Finally, several statistical approaches were used to superimpose human impacts on these natural controls in an attempt to evaluate the relative impacts of different trail users.

The REG (regression) process in SAS was used to develop bivariate and multiple regression models (Freund and Littell, 1986). The bivariate models compared water runoff and sediment yield with the continuous variables listed in Table 4. The multiple regression models incorporated the same continuous variables as well as indicator variables for soil texture and trail user (Table 4). The indicator variables divided the entire data set into four soil textural subgroups (clay, sandy clay, loam, and sandy loam) and five trail user subgroups (hiker, horse, off-road bicycle, motorcycle, and control). This procedure transformed soil texture and trail user into three and four indicator variables, respectively, and produced regression models that were capable of incorporating as many as five independent variables, seven indicator variables, and 75 new variables representing the cross-products of the continuous and indicator variables. This approach allowed the impacts of specific trail users to be differentiated from other trail users with respect to individual soil textures as well as the other measured variables.

In general, this method involves the sequential development of regression models in which statistically non-significant variables are eliminated. The SAS REG stepwise multiple regression procedure

Table 3. Comparison of Bouyoucos Mechanical and "Feel" Method Textures.

Method Sample[1]	Bouyoucos Method Percent Sand	Silt	Clay	Texture	"Feel" Texture
ELT1, Control, 0-6%	68	21	11	Sandy loam	Sandy loam
ELT1, Motorcycle, 0-6%	60	29	11	Sandy loam	Sandy loam
ELT3, Hiker, 8-21%	42	42	16	Loam	Loam
ELT1, Bicycle, 8-21%	60	31	9	Sandy loam	Sandy loam
ELT3, Bicycle, 0-6%	50	36	14	Loam	Loam
ELT1, Motorcycle, 8-21%	44	38	18	Loam	Loam
NWG2, Hiker, 8-21%	23	40	37	Clay loam	Clay loam
NWG2, Bicycle, 8-21%	19	36	45	Clay	Clay
NWG2, Horse, 0-6%	25	35	40	Clay	Clay loam
NWG3, Motorcycle, 0-6%	26	39	35	Clay loam	Clay loam
NWG3, Hiker, 0-6%	29	36	35	Clay loam	Clay loam
NWG3, Motorcycle, 8-21%	21	37	42	Clay	Clay

[1] ELT = Emerald Lake Trail; treatment type; and slope gradient (%).
NWG = New World Gulch Trail; treatment type; and slope gradient (%).

permitted the forward selection and backward elimination of non-significant variables until no further additions or deletions are permitted using the significance levels chosen by the user (Freund and Littell, 1986). The models developed to help explain water runoff and sediment yield variations in this study used the 0.05 significance threshold for both forward selection and backward elimination.

Although the multiple regression models described above provided information about the relative impacts of the different trail users to the extent that the indicator variables and interaction effects representing one or more trail users were incorporated in the final models, a more direct test was needed to assess the relative impacts of the different trail users. The multiple comparisons test within the GLM (General Linear Model) module of SAS was used to develop models which compared users in terms of water runoff and sediment yield. The SAS multiple comparisons test performs multiple difference of means tests and compiles the results in a series of tables (Freund et al., 1986). A 0.05 level of significance was used and the Bonferroni option was chosen because this option allows for comparisons of means from samples of unequal sizes. The means of the variables measured in

Table 4. Independent variables measured in study.

Indicator Variables

Soil texture class (clay, sandy clay, loam, and sandy loam)
Trail user (hiker, horse, off-road bicycle, motorcycle, and no activity)

Continuous Variables

Antecedent soil moisture
Slope
Soil resistance (soil compaction)
Trail roughness (trail micro-relief)
Water runoff (when sediment yield was treated as a dependent variable)

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the study were also replaced in the multiple comparisons test by least-squared means, because the latter estimate the class or subclass marginal means that would be expected had the study design been balanced (Freund et al., 1986). The use of 108 samples in this study (24 for hiking, horse, motorcycling and off-road bicycling, respectively; 12 for the control or null treatment case) meant the study design was not balanced.

RESULTS

3.1 Study Site Soil Descriptions

Soil profile descriptions for the soil pits located adjacent to the Emerald Lake and New World Gulch trail study sites are presented in Tables 5 and 6. The two in-trail soil profile descriptions differed from the off-trail descriptions with respect to the A and B_t horizons. The A horizons were missing (eroded) from both trail sites, so that the B_t horizons represented the soil surface. The removal of the A horizon on the Emerald Lake and New World Gulch trails meant that 5 and 7 cm of soil had been eroded by previous activity along the respective trails.

3.2 Water Runoff Scatterplots and Bivariate Regression Results

The first objective of the study was to determine what part of the variability of water runoff was statistically explained by the variability in topographic and soil variables. Table 7 summarizes the bivariate regression results for water runoff and four independent variables. The measurement of slope and antecedent soil moisture, trail roughness, and soil resistance prior to each rainstorm event meant that three sets of comparisons were possible; however, the relationships between these variables and water runoff produced similar regression results for all three data sets. Overall, these results show that none of the simple relationships between water runoff and slope, antecedent soil moisture, antecedent trail roughness and antecedent soil resistance respectively were statistically significant at the 0.05 significance level. The large scatter of points in the scatterplots reproduced in Figure 5 confirms this conclusion.

3.3 Water Runoff Multiple Regression Results

This situation did not change when multiple regression was substituted for the bivariate regression in that none of the independent variables were related to water runoff at the 0.05 significance level. Both the bivariate and multiple regression results suggest that the variability of water runoff cannot be statistically explained by the independent variables that were included, at least as they were measured in this study.

3.4 Sediment Yield Scatterplots and Bivariate Regression Results

The second objective of the study was to determine what part of the variability of sediment yield could be explained with the topographic, hydrologic, and soil variables. The same procedure used for the water runoff analysis was followed here except for the inclusion of water runoff as another independent variable.

The relationships between sediment yield and the slope and trail roughness independent variables were statistically significant at the 0.01 level (Table 8). This table is divided into three parts to distinguish rainstorms on dry soils (n=60), rainstorms on pre-wetted soils (n=108), and all rainstorms events (n=168). Variations in slope and antecedent trail roughness explained 12.7 and 10% of the variability in sediment yield, respectively when all the plots were examined. The results were similar for all three groups of rainstorms because sediment yield (like water runoff in the previous section) was not statistically related to variations in antecedent soil moisture. The large scatter of points in all five scatterplots reproduced in Figure 6 confirms that the variability in sediment yield was only partially explained by the variables measured in this study. These results indicate the complexity that must be understood to decipher how the natural controls of water runoff and sediment yield operate on existing trails.

Table 5. Off-trail soil profile description near Emerald Lake trail study site.

Depth (cm)	Horizon	Color moist[1]	Texture[2]	Structure[3]	Consistence[4]	Roots	Coarse frags.	pH
0-5	A	10yr 2/2	sl	single grain	lo fr so	common vfine	none	4.5
5-22	Bt	10yr 2/2	sl	abk(sub) fine mod.	sh fr ss	common vfine	10%	6.0
22-55	C1	10yr 4/6	gs	single grain	lo lo so	none	50%	6.5
55+	C2	10yr 3/4	gsl	single grain	lo fr so	none	30%	6.0

1 Represents the color of the soil when moist. Looking at the A horizon, for example, 10yr represents hue or gradation of color, the first 2 represents the value or the lightness or darkness of the color, and the second 2 represents the chroma or the strength and purity of the color.

2 Texture of the soil: sl, gs, and gsl represent sandy loam, gravelly sand and gravelly sandy loam, respectively.

3 Structure of the soil horizon: abk(sub) fine moderate represents a subangular blocky structure with moderate or easily observable blocks and sizes between 5 and 10 mm.

4 Consistence is a measure of the soil's ability to adhere or cohere. This property was measured for dry, moist, and wet samples abbreviations: Dry-lo, loose; sh, slightly hard; Moist- fr, friable, lo, loose; and Wet-so, nonsticky; ss, slightly sticky.

3.5 Sediment Yield Multiple Regression Results

The multiple regression results for sediment yield summarized in Table 9 show that five independent variables explained 42% of the variability in sediment yield. The first four variables in Table 9 indicate that steeper slopes and the plots with the most clay and terrain variability (roughness) produced the most sediment yield. These four cross-product variables explained 41% of the

Table 6. Off-trail soil profile description near New World Gulch trail study site.

Depth (cm)	Horizon	Color moist[1]	Texture[2]	Structure[3]	Consistence[4]	Roots	Coarse frags.	pH
0-7	A	2.5yr 2.5/4	sc	abk f,vf mod.	h fi s	common fine	<1%	8.0
7-38	Bt_1	2.5yr 3/4	sc	abk fine mod.	h vfi vs	few vfine	1%	8.0
38-73	Bt_2	2.5yr 2.5/4	sc	abk f,vf mod.	h vfi vs	none	1%	7.5
73+	C	2.5yr 3/6	sl	abk fine mod.	h fi s	none	2%	8.0

1 Represents the color of the soil when moist. Looking at the A horizon, for example, 2.5YR represents the hue or gradation of color, 2.5 represents the value or the lightness or darkness of the color, and the 4 represents the chroma or the strength and purity of the color.

2 Texture of the soil: sc and sl represent sandy clay and sandy loam.

3 Structure of the soil horizon: abk fine moderate represents an angular blocky structure with the moderate or easily or observable blocks and sizes between 5 and 10mm.

4 Consistence is a measure of the soil's ability to adhere or cohere. This property was measured for dry, moist, and wet samples abbreviations: Dry-h, hard; sh, slightly hard; Moist-fi, firm, vfi- very firm; and Wet-s, sticky, vs, very sticky.

variability in sediment yield. Steep slopes have been positively correlated with sediment yield in many environments (e.g., Wischmeier and Smith, 1978) and the combination of trail roughness and sandy clay soils presumably indicates increased availability of sediment for removal. The final variable combines soil moisture and loam soils, but this variable only explained 1% of the remaining variability in sediment yield.

Table 7. Bivariate regression results treating water runoff as the dependent variable.

	First rainstorm (n=60)		Second rainstorm (n=108)		All rainstorms (n=168)	
Variable	R^2	P Value	R^2	P Value	R^2	P Value
Slope	.012	.41	.002	.69	.0004	.58
Antecedent soil moist.	.0002	.92	.002	.66	.0001	.60
Antecedent trail roughness	.0001	.79	.003	.61	.0001	.93
Antecedent soil density	.002	.74	.004	.55	.0001	.69

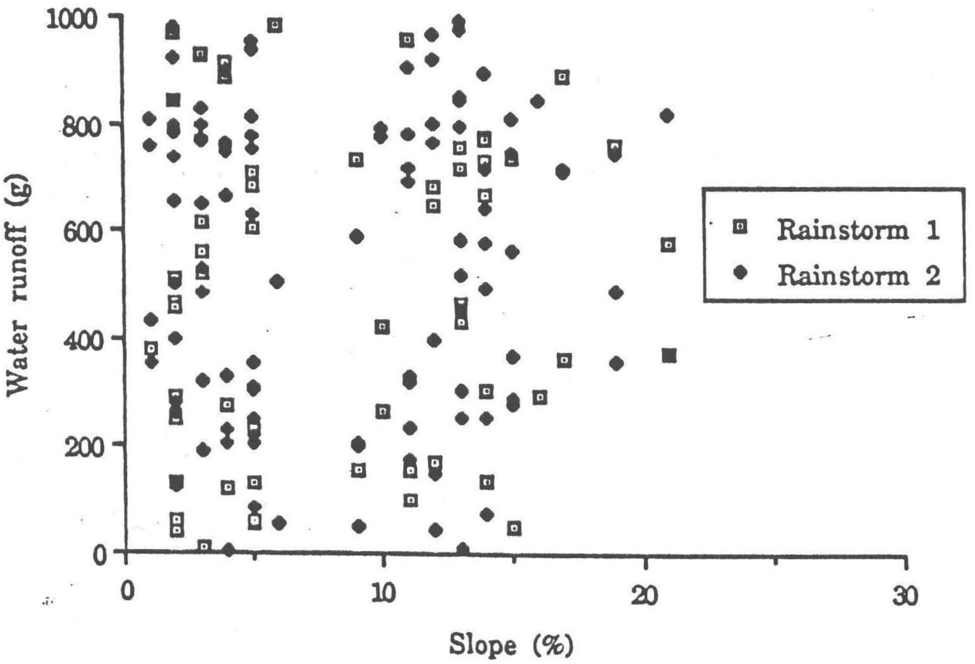
3.6 Relative Impacts

Three approaches were used to determine the relative impacts of different trail uses on water runoff and sediment yield: 1) the development of several multiple regression models that included trail use as a series of indicator variables; 2) the comparison of water runoff and sediment yield means by user type; and 3) the comparison of soil resistance and trail roughness changes by user type over time.

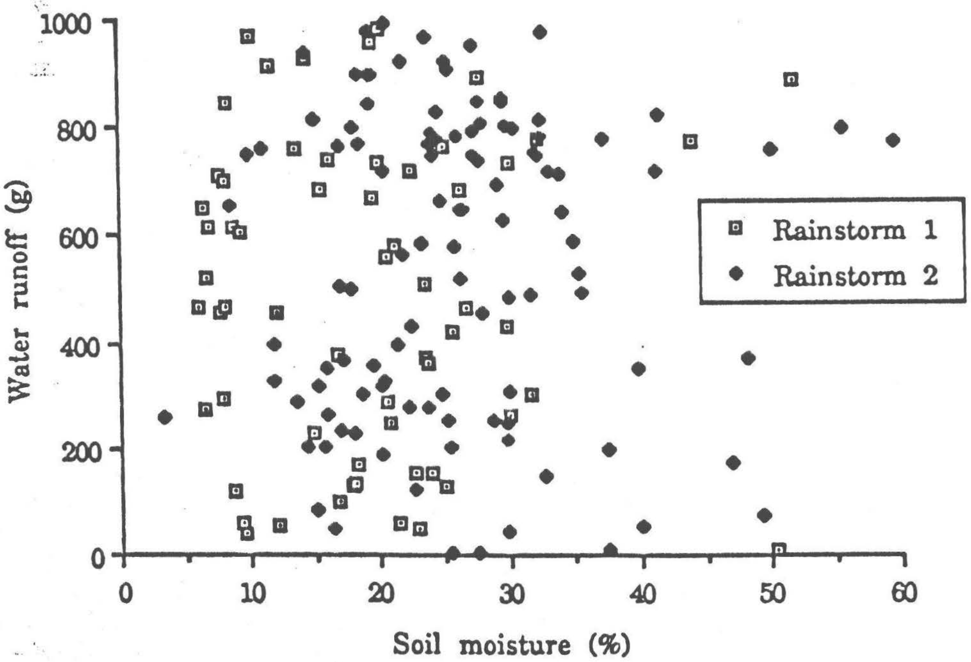
Multiple Regression Results

Two sets of indicator variables were used in the multiple regression models developed to differentiate four textural classes (as before) and five trail user classes in this part of the study. The addition of four new indicator variables to accommodate trail use meant that four continuous variables, seven indicator variables and 60 cross-products were considered with water runoff as the dependent variable and that five continuous variables, seven indicator variables, and 75 cross-products were considered with sediment yield as the dependent variable. Both models used the results from the second rainstorms (n=108), since these rainstorms followed user treatments (Table 2).

None of the independent variables were related to water runoff at the 0.05 significance level. This result suggests (once again) that the variability of water runoff cannot be statistically

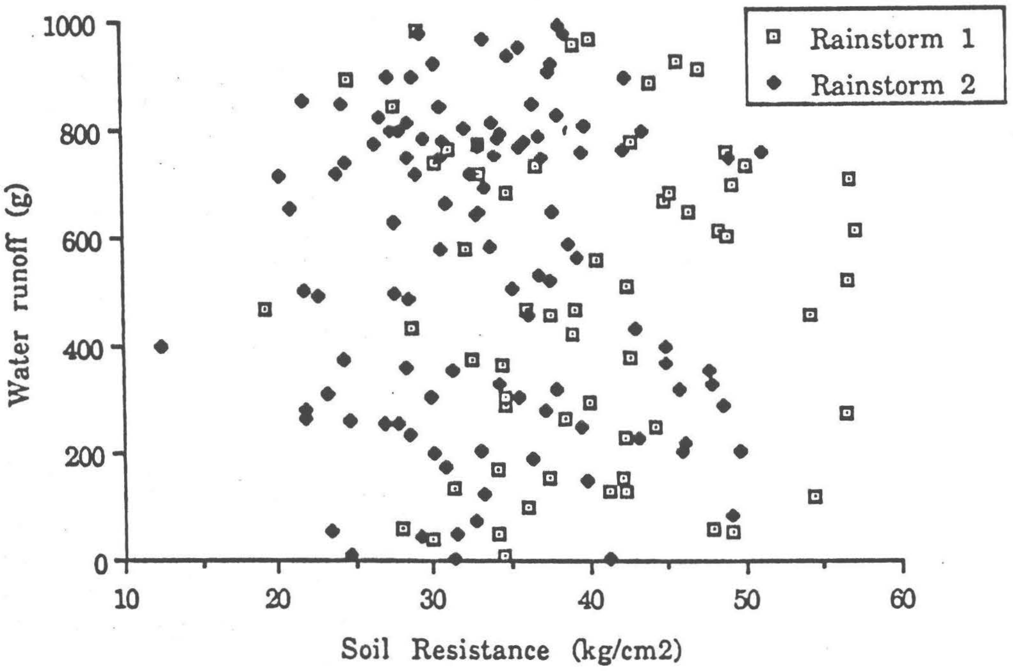


A. Water runoff versus slope.

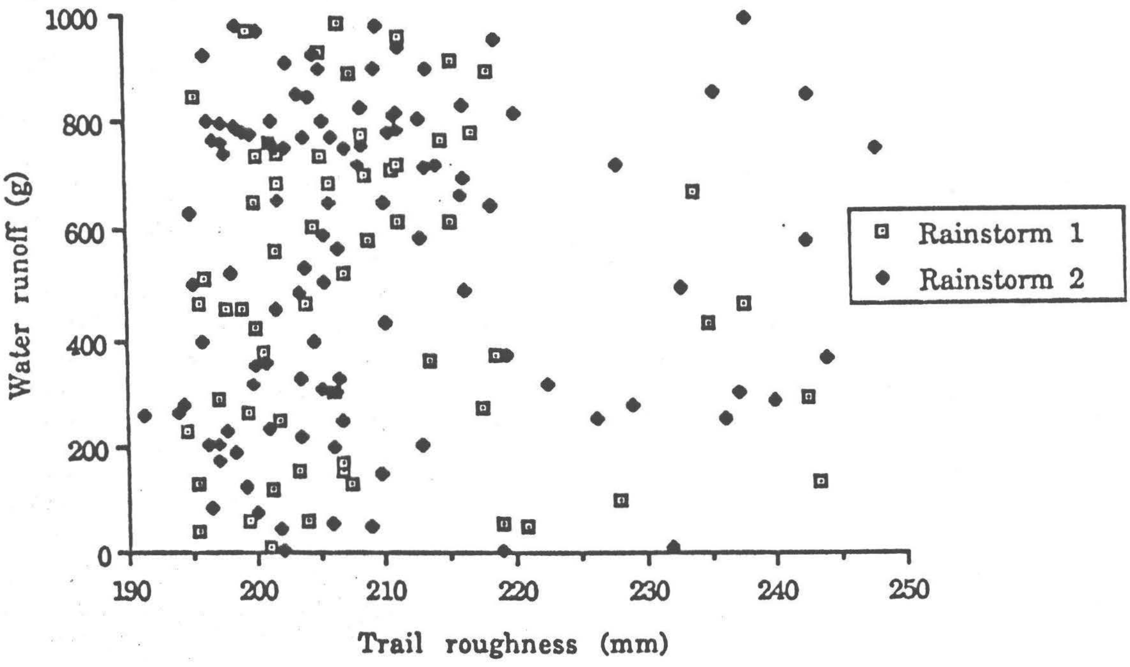


B. Water runoff versus antecedent soil moisture.

Figure 5. Scatterplots for water runoff and selected variables.



C. Water runoff versus antecedent soil resistance.



D. Water runoff versus antecedent trail roughness.

Figure 5. Scatterplots for water runoff and selected variables (continued).

Table 8. Bivariate regression results treating sediment yield as the dependent variable.

	First rainstorm (n=60)		Second rainstorm (n=108)		All rainstorms (n=168)	
Variable	R^2	P Value	R^2	P Value	R^2	P Value
Slope	.117	.01	.139	.01	.127	.01
Antecedent soil moist.	.023#	.34	.038	.11	.022	.12
Antecedent trail roughness	.125	.01	.091	.01	.100	.01
Antecedent soil density	.024	.41	.003	.33	.010	.35
Water runoff	.026	.29	.001	.79	.001	.59

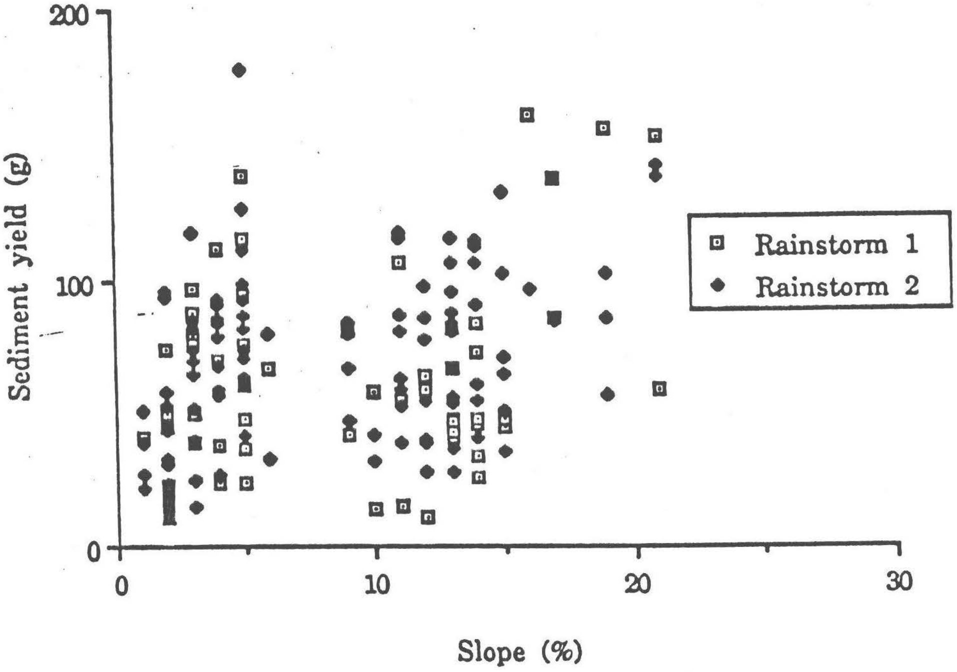
represents inverse relationship

explained by the independent variables that were included, at least as they were measured in the study.

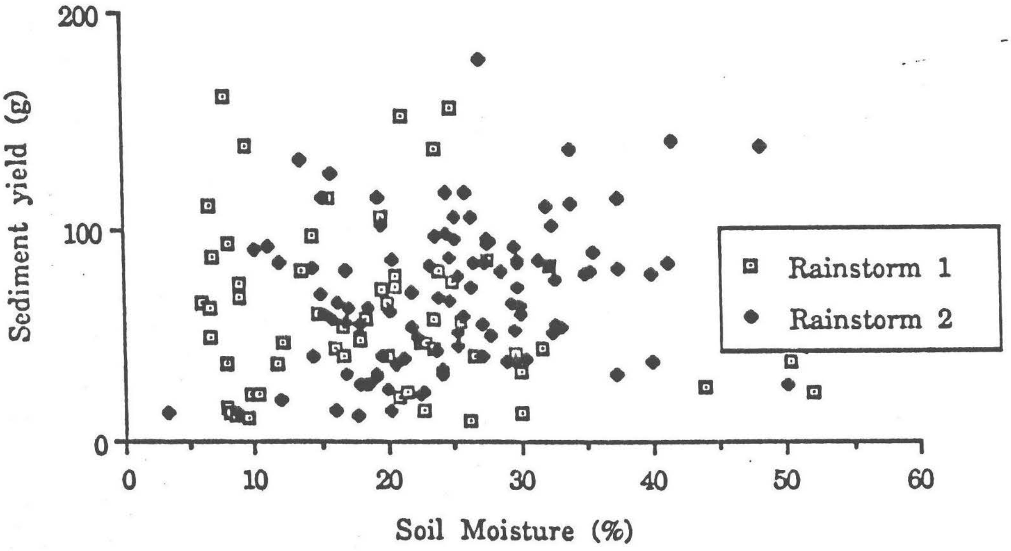
Ten variables explained 70% of the variability in sediment yield from the sample plots (Table 10). This regression model included three interaction variables with one indicator variable (Soil Moisture*Clay), and seven interaction variables two indicator variables and one continuous variable (e.g., Water Runoff*Clay *Horse). The Slope variable represents an interaction of the continuous variable slope and the default case for both series of indicator variables (i.e., soil texture and user treatment).

This model clearly is better than the model without trail user. Overall, the same variables explained most of the variability in sediment yield. Hence various combinations of slope, trail roughness and clay (with horses) explained 46% of the variability by themselves and soil texture was part of all seven of the cross-products that explained another 24% of the variability. Soil moisture, water runoff, and slope appeared in four, two, and one of the cross-products in the second group, respectively.

This particular model was different from the earlier one such that five trail treatments, represented by four additional indicator variables and 60 cross-products, were added. The 28% increase in the overall R^2 (from 42% to 70%) must be attributed to the inclusion of this second series of indicator variables and not surprisingly, one or more of these indicator variables appeared in seven of the ten significant independent variables in the regression model (Table 10). The contributions of the different variables to the ten significant independent variables to the final result (R^2 = 70%) provided a rough guide of their cumulative impacts and confirmed that three variables stood out: soil texture

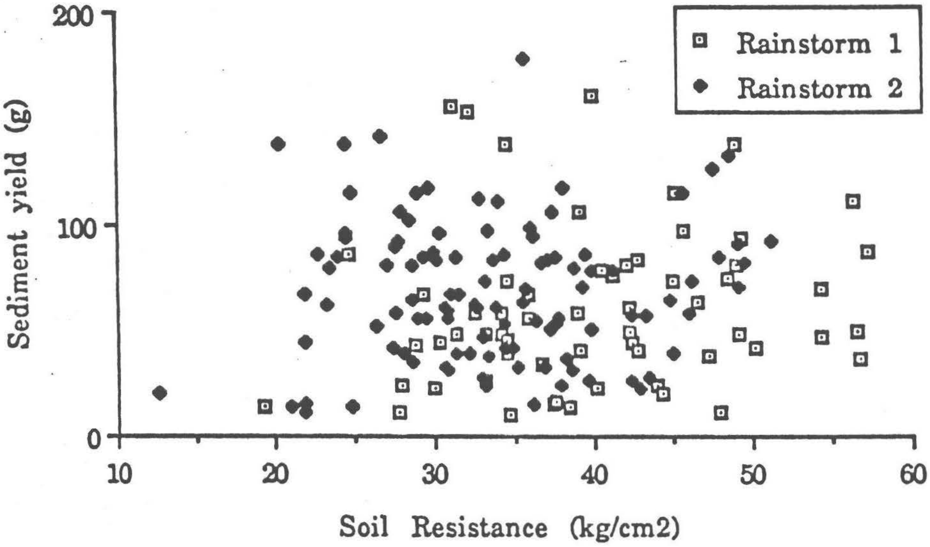


A. Sediment yield versus slope.

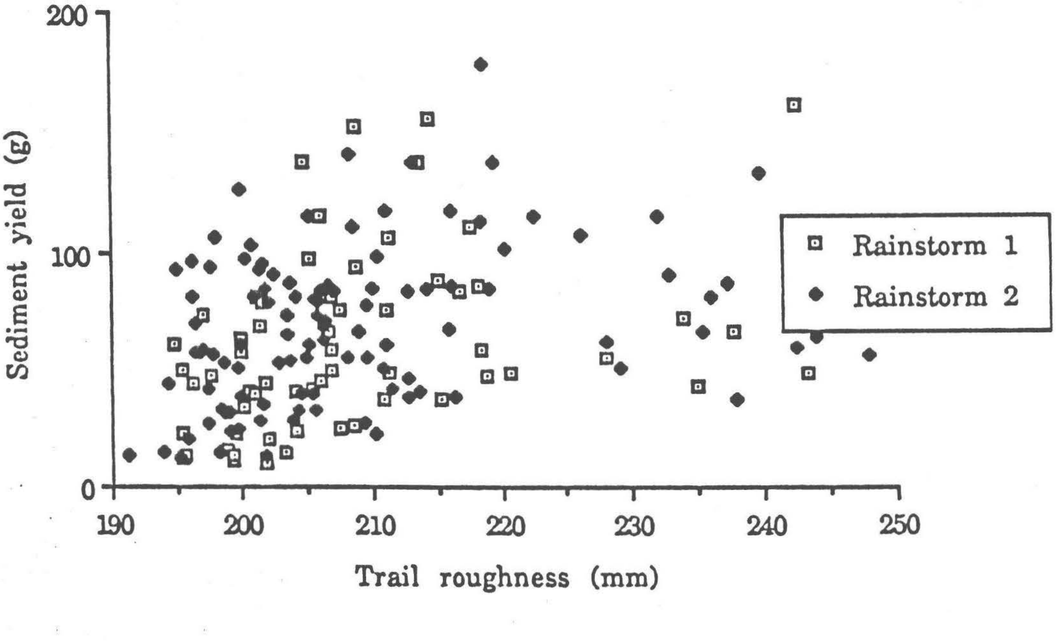


B. Sediment yield versus antecedent soil moisture.

Figure 6. Scatterplots of sediment yield and selected variables.

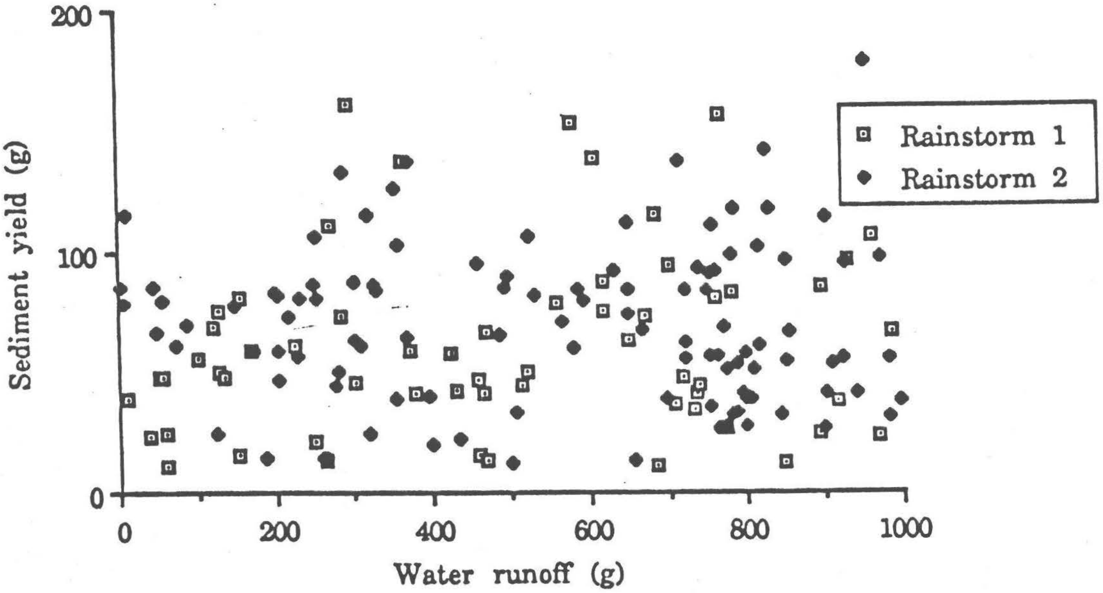


C. Sediment yield versus antecedent soil resistance.



D. Sediment yield versus antecedent trail roughness.

Figure 6. Scatterplots of sediment yield and selected variables (continued).



E. Sediment yield versus water runoff.

Figure 6. Scatterplots of sediment yield and selected variables (continued).

(37%), slope (35%), and user treatment (35%). Soil moisture, trail roughness (both 13%), and water runoff (9%) made much smaller contributions and soil resistance did not show up at all.

User treatments, of course, are of most interest here and following the last approach, their contributions to the ten significant independent variables can be isolated as follows: horse (appears 4 times that explain 26% of the variability in sediment yield), motorcycle (2 times; 6%), and hiker (1 time; 3%). It is very difficult to take this type of analysis further, although certain relationships are suggested. Some examples follow: the Slope*Horse cross-product appears to increase sediment yield (partial R^2 = 15%) but the cross-product Slope*Clay*Motorcycle decreases sediment yield (partial R^2 = 2%). Soil moisture appears to increase sediment yield when the cross-product includes clay (partial R^2 = 4%) or loam and motorcycle use (partial R^2 = 4%) but appears to decrease sediment yield when combined with Clay*Hiker (partial R^2 = 3%) and Sandy Loam*Horse (partial R**2 = 2%). Clearly, the user type helps to explain sediment yield from the experiments conducted, although distinguishing the contributions of the specific treatments clearly requires a different approach.

Table 9. Sediment yield multiple regression results.

Variable	Parameter estimate	Partial R^2	Model R^2	Prob>F	F
Intercept	30.64			0.0001	29.11
Slope*clay[1]	5.79	0.18	0.18	0.0001	15.85
Trail roughness* sandy clay[2]	0.20	0.17	0.35	0.0001	48.53
Slope	1.49	0.04	0.39	0.0055	7.91
Trail roughness* clay3	0.23	0.02	0.41	0.0231	5.26
Soil Moisture* loam4	0.39	0.01	0.42	0.0411	4.24

1 Slope*clay represents the slope continuous variable and the clay indicator variable cross-product.

2 Trail roughness*sandy clay represents the trail roughness continuous variable and the sandy clay indicator variable cross-product.

3 Trail roughness*clay represents the trail roughness continuous variable and the clay indicator variable cross-product.

4 Soil moisture*loam represents the soil moisture continuous variable and the loam indicator variable cross-product.

Multiple Comparison Test Results

The multiple comparison test in SAS was used to perform a series of difference of means tests and assess the relative impacts of the different trail users with respect to water runoff and sediment yield. However, the water runoff and sediment yield means compiled by treatment type were replaced by least-squared means in these tests for the reasons noted in Methods. Table 11 shows the p values as well as the least squared water runoff means by treatment type. The p values indicate the probability (likelihood) that different pairs of means are different such that a value of 0.05 or less indicates two statistically significant different means using a 0.05 level of significance.

Clearly, there are no statistically significant different pairs of means for water runoff (Table 11). This result is reassuring in the case of the first subset since the result confirms that the trails used for the five treatments were similar in terms of their water runoff behavior prior to the treatments. In other words, the sample design used in this study did not introduce any significant bias into the results. The results in

Table 10. Sediment yield multiple regression results.

Variable	Parameter estimate	Partial R^2	Model R^2	Prob>F	F
Intercept	29.33			0.0001	46.96
Slope[1]	1.72	0.18	0.18	0.0001	15.01
Slope*horse[2]	2.18	0.15	0.33	0.0001	16.81
Trail roughness*clay[3]	0.21	0.13	0.46	0.0001	77.74
Water runoff*sand clay*horse[4]	0.15	0.05	0.51	0.0001	20.66
Water runoff*loam* horse[5]	0.06	0.04	0.55	0.0005	12.86
Soil moisture*clay[6]	1.17	0.04	0.59	0.0001	27.31
Soil moisture*loam* motorcycle[7]	0.91	0.04	0.63	0.0001	17.93
Soil moisture*clay* hiker[8]	-1.04	0.03	0.66	0.0012	11.17
Soil moisture*sandy clay*horse[9]	-2.12	0.02	0.68	0.0039	8.73
Slope*clay* motorcycle[10]	-4.60	0.02	0.70	0.0142	6.24

1 Slope represents the slope continuous variable and the default case for both series of indicator variables.

2 Slope*horse represents the slope continuous variable and horse indicator variable cross-product.

3 Trail roughness*clay represents the trail roughness continuous variable and clay indicator variable cross-product.

4 Water runoff*sandy clay*horse represents the water runoff continuous variable and clay and horse indicator variable cross-products.

5 Water runoff*loam*horse represents the water runoff continuous variable and loam and horse indicator variable cross-products.

6 Soil moisture*clay represents the soil moisture continuous variable and clay indicator variable cross-product.

7 Soil moisture*loam*motorcycle represents the soil moisture continuous variable and loam and motorcycle indicator variable cross-products.

8 Soil moisture*clay*hiker represents the soil moisture continuous variable and clay and hiker indicator variable cross-products.

9 Soil moisture*sandy clay*horse represents the soil moisture continuous variable and sandy clay and horse indicator variables cross-products.

10 Slope*clay*motorcycle represents the slope continuous variable and clay and motorcycle indicator variable cross-products.

Table 11. Water runoff multiple comparison results.

User Treatment	Mean water runoff (g)	Bicycle	Control	Hiker	Horse	Motorcycle
				p values		
A. Prior to User Treatments (n = 54)						
Bicycle	4650	N/A[1]				
Control	4498	0.70	N/A			
Hiker	4713	0.88	0.60	N/A		
Horse	4507	0.72	0.98	0.59	N/A	
Motorcycle	4889	0.57	0.37	0.66	0.33	N/A
B. After User Treatments, Prewetted Plots (n = 54)						
Bicycle	5619	N/A				
Control	5862	0.46	N/A			
Hiker	5767	0.67	0.78	N/A		
Horse	5628	0.98	0.48	0.66	N/A	
Motorcycle	5730	0.75	0.72	0.91	0.76	N/A
C. Prior Minus After, User Treatments (n = 54)						
Bicycle	219	N/A				
Control	216	0.99	N/A			
Hiker	148	0.74	0.74	N/A		
Horse	-140	0.07	0.07	0.12	N/A	
Motorcycle	-173	0.07	0.07	0.10	0.86	N/A
D. User Treatments on Dry Plots (n = 54)						
Bicycle	4659	N/A				
Control	4550	0.73	N/A			
Hiker	4720	0.82	0.58	N/A		
Horse	4462	0.42	0.77	0.31	N/A	
Motorcycle	4478	0.48	0.82	0.34	0.95	N/A

[1] N/A represents no result

Parts B through D of Table 11 confirm the multiple regression results in that they show that user type did not significantly alter runoff behavior.

Table 12 displays the sediment yield p values as well as the least squared sediment yield means by treatment type. The results are more substantial than the water runoff results because there are some statistically significant differences at the 0.05 level of significance. The results from Part A suggest that the trails used for the five treatment types were not similar in terms of their sediment yield behavior prior to the treatments. Trail plots used for hikers were statistically different from one of the other groups (off-road bicycles) at the 0.05 level of significance, and all groups if one uses the 0.15 level of significance. Thus, the sample design did incorporate some bias for the sediment yield results. The results from Part A in Tables 11 and 12 indicate that less sediment was available for detachment and entrainment on the hiker plots since water runoff generated from the plots used for the different treatments prior to the user treatments themselves were not significantly different.

The sediment yields reported in Part B of Table 12 indicate that horse plots produced significantly more sediment than the bicycle, control, and hiker trail plots at the 0.05 level of significance, presumably due to an increase in sediment availability. Trail plots used by motorcycle were statistically significant from one of the other groups (hiker) at the 0.05 level of significance and bicycle and control trail plots if one uses the 0.15 level of significance.

The results in Part C of Table 12 indicate the need to exercise caution when looking at the results. This part of the table summarizes the mean differences between the sediment yields produced from the prewetted and post treatment rainstorms by user. These comparisons are important because the hiker plots were significantly different from the outset. These data show that horse plots are different from the bicycle and hiker plots at the 0.05 and 0.10 levels of significance, respectively. This result focuses attention on the differences due to the treatments; most importantly, it reduces the number of significant results from Part B, presumably because it removes some or possibly all of the bias inherent in the original data. Hikers, therefore, produced the second largest increase in sediment yield following horse treatments, and overall the horse and hiker differences indicate that hooves and feet make more sediment available for removal than wheels on prewetted soils.

The results in Part D of Table 12 indicate horse plots produced significantly more sediment than did bicycle, hiker, and motorcycle plots at the 0.05 level of significance on the dry plots as well. The final test will be to look at changes through time to see whether or not changes in soil resistance and trail roughness substantiate the interpretation that horse plots produce the greatest net change on sample plots used in the study.

Changes in Soil Resistance and Trail Roughness Through Time

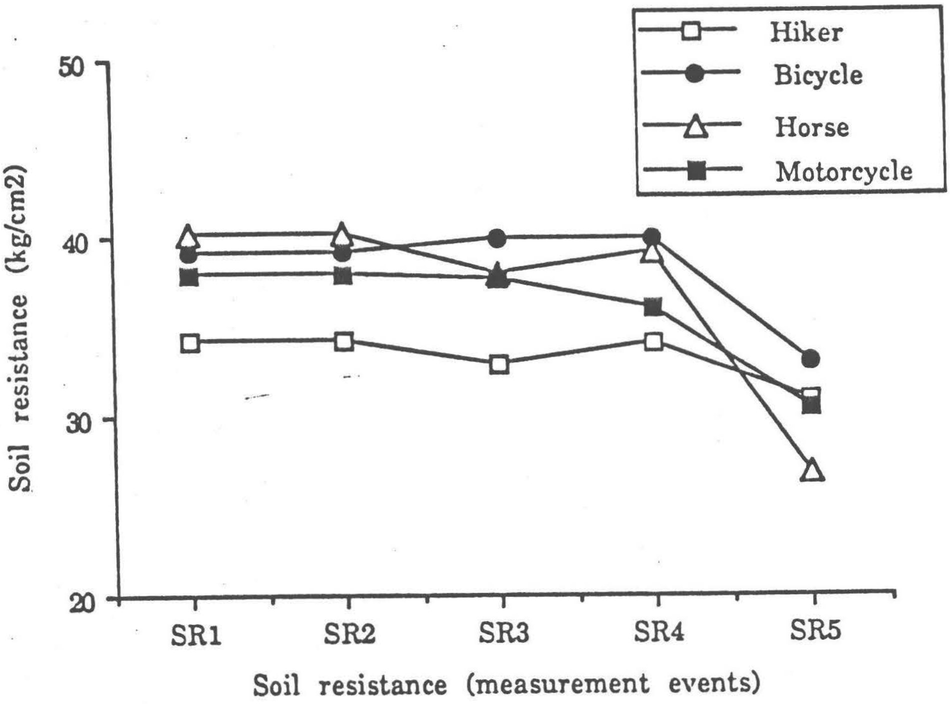
Figure 7 shows changes in soil resistance through time by treatment type in which SD1, SD2, SD3, SD4, and SD5 represent soil resistance measurements taken when the plot was first selected, following the prewetting rainstorm (only for prewetted treatments),

Table 12. Sediment yield multiple comparison results.

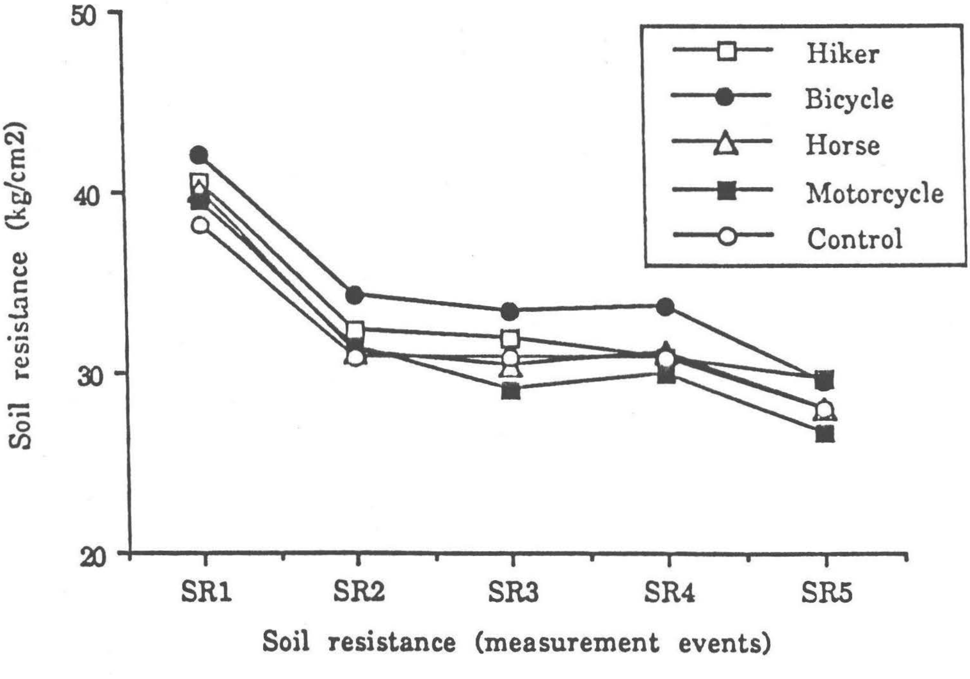
User Treatment	Mean sediment yield (g)	Bicycle	Control	Hiker	Horse	Motorcycle
				p values		
A. Prior to User Treatments (n = 54)						
Bicycle	69	N/A[1]				
Control	59	0.46	N/A			
Hiker	38	0.04	0.14	N/A		
Horse	60	0.53	0.93	0.11	N/A	
Motorcycle	65	0.81	0.67	0.06	0.70	N/A
B. After User Treatments, Prewetted Plots (n = 54)						
Bicycle	63	N/A				
Control	65	0.81	N/A			
Hiker	63	0.98	0.80	N/A		
Horse	96	0.01	0.01	0.01	N/A	
Motorcycle	83	0.06	0.08	0.04	0.18	N/A
C. Prior minus After, User Treatments (n = 54)						
Bicycle	-2	N/A				
Control	7	0.57	N/A			
Hiker	21	0.19	0.38	N/A		
Horse	34	0.03	0.09	0.40	N/A	
Motorcycle	15	0.33	0.64	0.70	0.24	N/A
D. User Treatments on Dry Plots (n = 54)						
Bicycle	58	N/A				
Control	61	0.68	N/A			
Hiker	55	0.76	0.49	N/A		
Horse	75	0.02	0.16	0.01	N/A	
Motorcycle	59	0.89	0.76	0.65	0.03	N/A

1 N/A represents no result

following the first 50 passes, another 50 passes, and after the second rainstorm. The changes through time for dry treatments indicate that 50 bicycle passes increased soil resistance, whereas the other three users decreased soil resistance. The application of the second 50 bicycle, hiker, and horse passes increased soil resistance, although soil resistance on motorcycle plots decreased. The most dramatic change occurred as a result of rainfall. Soil



A. Changes in soil resistance on dry trail plots.



B. Changes in soil resistance on prewetted trail plots.

Figure 7. Changes in soil resistance through time.

resistance decreased noticeably for dry and prewetted plots following each rainstorm (SR2, SR5 and SR5 for prewetted and dry plots, respectively). Overall, these results provide few clues about why different users produced statistically significant and different sediment yields.

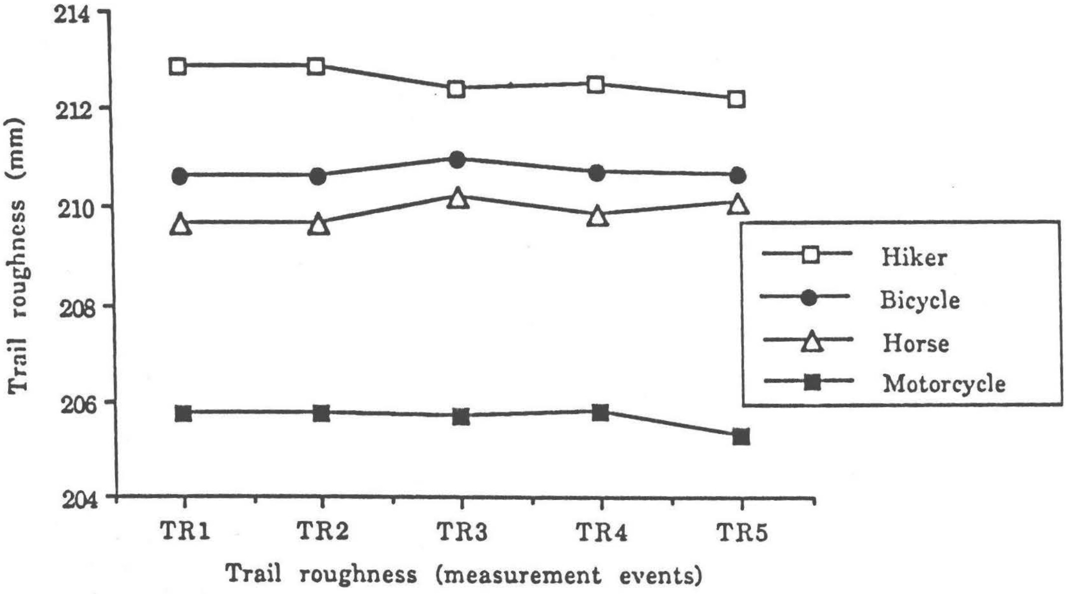
Figure 8 shows changes in trail roughness through time by treatment type in which TR1, TR2, TR3, TR4, and TR5 represent trail roughness measurements taken when the plot was first selected, following the first rainstorm (only for prewetted trail plots), following the first 50 passes, another 50 passes, and after the second rainstorm. Trail roughness on dry trail plots showed little net change and in some respects produced contradictory results. For example, the first 50 hiker passes decreased trail roughness and the second 50 passes increased roughness. Similarly, the first 50 bicycle and horse passes increased and the second 50 passes decreased trail roughness. Trail roughness changes on prewetted plots were more pronounced. Fifty bicycle and horse passes decreased trail roughness, whereas 50 hiker passes increased trail roughness. The application of the second 50 bicycle, horse, and hiker passes decreased trail roughness with the most dramatic decreases occurring on horse and hiker plots. Trail roughness increased following the application of the final rainstorm on the bicycle, horse, hiker, and motorcycle plots, with horse plots showing the greatest net change. The trail roughness results (like the soil resistance results) provide few insights about why different users produced statistically significant and different sediment yields.

DISCUSSION

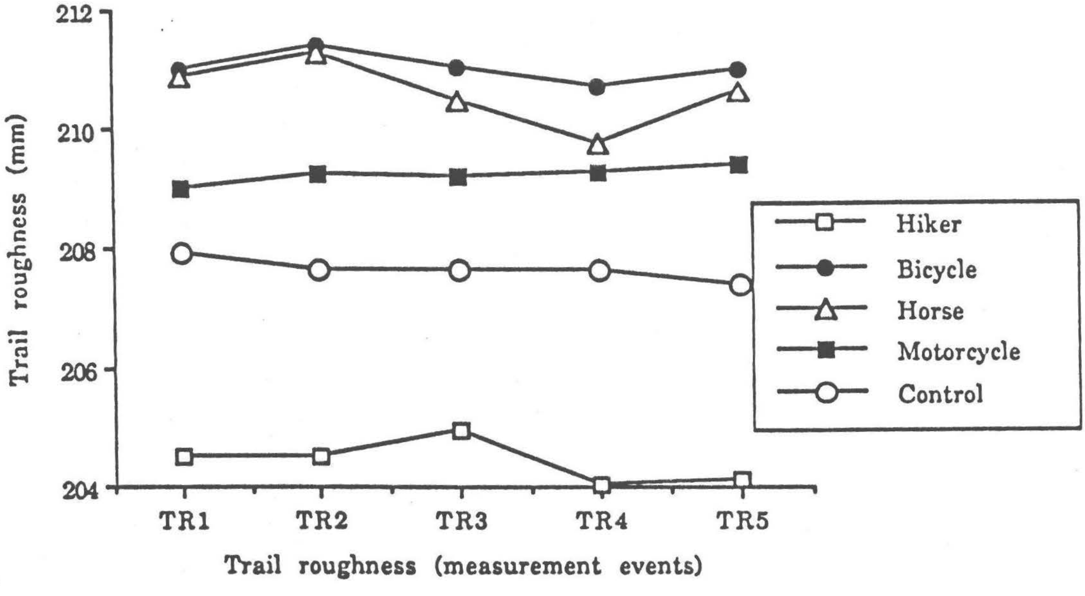
4.1 Regression Analysis

An understanding of the natural processes and controls operating on trails is necessary before trail users can be added and their impacts isolated from those of the physical site characteristics (Weaver and Dale, 1974; Helgath, 1975; Bratton et al., 1979; Quinn et al., 1980; Summer, 1980 and 1986; Jubenville and O'Sullivan, 1987; Kuss, 1987). This study demonstrates the complexity of topographic, soil, and geomorphic variables and the difficulty of quantifying these effects and relationships. The results do confirm and/or clarify some of the important relationships between trail users and water runoff and sediment yield identified in other studies, and the following discussion focuses on the broader significance of these results.

Bivariate and multiple regression reveal no significant relationships between water runoff and the variables of slope, soil texture, antecedent soil moisture, trail roughness, and soil resistance. There are two possible explanations: (1) the study did not measure the variables in ways that the natural variability of



A. Changes in trail roughness on dry trail plots.



B. Changes in trail roughness on prewetted trail plots.

Figure 8. Changes in trail roughness through time.

the sample plots could be expressed, and/or (2) the study did not measure all the relevant variables.

The first explanation may apply to the antecedent soil moisture, trail roughness, and soil resistance measurements. Trail roughness, for example, may not have been sampled frequently enough (each time) to accurately quantify the roughness of the plot surfaces. Trail roughness encourages ponding and therefore may increase residence time and infiltration, and thereby reduce runoff. The density (number) of measurements (each time) may have been too few to capture this effect. Similar problems may have affected the antecedent soil moisture and soil resistance measurements. Hence, these variables may not have been measured at enough sites to estimate their spatial variability and their impact on infiltration rates and therefore runoff volumes.

Two potentially important variables (elapsed time of water application, and the swelling properties of clays found at the New World Gulch site) were not measured. Although 41.75 mm of water was applied in every case, the application time varied between 20 and 23 minutes. This variability meant that the application rate was reduced as much as 15% (109 mm hr^{-1}) compared to the desired rate of 127 mm hr^{-1}. Most of these problems occurred on the New World Gulch trail, since these sample plots were located beside a stream which carried a considerable stream sediment load. The practice of allowing the water to settle and using only the upper portion of water in the container was able to prevent most but not all of the sediment from being processed through the rainfall simulator. This state of affairs meant that some of the needles used as drip formers by the rainfall simulator were blocked for some applications. The potential impact was the same as with the measurement problems noted above since lower intensities may produce more infiltration and less runoff.

The failure to (1) examine the clay mineralogy at the different sites and (2) incorporate these results in the regression analysis may represent another important omission. Smectites (swelling clays) are present at the New World Gulch sample plots. These clays can absorb more water than non-swelling clays and hence the clay mineralogy may have helped to decipher some of the differences in runoff behavior between plots.

The bivariate and multiple regression results were more successful in explaining the variability in sediment yield. Slope (R^2 = 12.7%) and antecedent trail roughness (R^2 = 10%) were significant independent variables when bivariate models were developed. Five independent variables or cross-products combined to explain 42% of the variability in sediment yield when multiple regression was used. Soil texture (introduced as a series of indicator variables), slope, and antecedent trail roughness were part of four, two, and two of these terms, respectively. The influence of slope and soil characteristics on trail erosion has been documented in other studies (Bryan, 1977; Weaver and Dale, 1978; Bratton et al., 1979; Klock and McColley, 1978; Quinn et al., 1980; Coleman, 1981; Fish et al., 1981; Kuss, 1983 and 1987; Jubenville and O'Sullivan, 1987).

Perhaps the most important discovery was the failure of water runoff to explain any of the variability in sediment yield, either by itself or as one of the terms in one or more of the cross-products. This result presumably indicates that sediment yield from existing trails is detachment rather than transport-limited. The exploration of the relative impact results confirms this state of affairs, and these results and their implications are examined next.

4.2 Relative Impact Analysis

Four new indicator variables and their cross-products were added to the multiple regression models noted above to examine the relative impacts of the different trail uses. There were two major findings: (1) no significant relationships were uncovered between water runoff and the indicator variables (as noted earlier), and (2) 10 variables combined to explain 70% of the variability in sediment yield. This second result is impressive and once again it shows that sediment yield is probably detachment limited for the two trails examined in the study. Treating the cumulative contributions of the different variables to the final result ($R^2 = 0.70$) as a rough guide of their importance confirmed that soil texture (37%), slope, (35%), and user treatment (35%) had the most impact. Water runoff (9%) was one of three variables that made smaller contributions. The importance of soil texture and slope in this and other studies has already been noted. However, the contribution of treatment type and the limited role of water runoff tend to confirm that sediment yield is detachment rather than transport-limited.

The multiple comparisons test results further clarify the roles of the different treatments and in particular show that horses and hikers (hooves and feet) make more sediment available than wheels (motorcycles and off-road bicycles) on prewetted trails. Reviewing the data in Table 12 shows that only horses stand out from the other treatments in terms of sediment production and that the other treatments produced no significant differences. Three problems with the study design may explain the lack of statistically significant differences between these other treatments. Two of the problems have to do with the concept of geomorphic thresholds and the third with mechanical removal of sediment from the sample plots.

Schumm (1977) noted that under different external and internal stress conditions there could be a dramatic change in geomorphic systems and significant alterations of the landscape. The minimum energy that must be applied varies with the environment, hence threshold values vary. Kuss (1987) applied this concept to recreational trails, noting that almost any rainstorm or level of use would impact new trails but that very large storms and/or very heavy use is needed to initiate change on existing trails. This threshold level varies depending on the type and quantity of use along with climatic, soil, and topographic variables. Two problems with the current study may have inhibited our ability to distinguish between hiker, off-road bicycle, and motorcycle uses: (1) the limitations of the rainfall simulator, and (2) the small number (100 passes) of treatments.

The most important limitation with the modified Meeuwig rainfall simulator is that it produces rainstorms of only one-third the intensity of natural rainstorm events. This relationship was very evident comparing simulated and natural rainstorm events in the field. There was a very noticeable difference in the quantities of water runoff flowing down the trail from these events compared to the rainfall simulator events. The impact of rainfall intensity on the relationships between the pre-existing trail condition (i.e., trail history) and sediment production, and threshold values is not obvious. However, the restrictions placed upon the duration and intensity of the rainstorms applied in this study decreased the likelihood that thresholds values were attained, especially since the study focused exclusively on existing trail segments.

The application of only 100 passes (for all four treatments) probably contributed to the failure to attain the appropriate thresholds for all but horse traffic. Lull (1959) suggested impact per unit area could help account for the relative impacts of different trail uses. Horses produce the greatest impact per unit area and as a result, horses appeared to produce the greatest net change in this study. Other treatments may not have been applied enough times and/or in conjunction with long and/or heavy enough simulated rainstorms for statistically significant differences to show up between the other treatment types.

The failure to measure the quantities of soil removed with (stuck to) feet and tires from the prewetted plots may have contributed to the lack of statistically significant differences between the hiker, motorcycle, and bicycle plots that were uncovered as well. The mechanical removal of sediment in these ways was observed on most prewetted plots and in some cases most of the moist soil was removed from the sample plot and a dry soil surface was exposed as the treatment was applied. The quantities of sediment removed in these ways were not measured when clearly these losses need to be combined with those that were measured in order to quantify the relationships between sediment yield and trail roughness, soil resistance and other variables more precisely.

Despite these problems, two sets of findings emerge from this study which probably apply to many (if not most) environments. First, horses produced greater sediment yields then the other trail uses. Several other studies (Dale and Weaver, 1974; Weaver and Dale, 1978; Bratton et al., 1979) reached similar conclusions, although further comparisons are difficult because of differences in study designs. The second major finding from this study is that the largest and most frequent changes tended to occur on prewetted trails. This result occurs because the application of rainfall and the increase in soil moisture which follows reduces soil resistance, which, in turn, reduces the trail's ability to bear a moving load. Helgath (1975), Bryan (1977), Weaver and Dale (1978), Bratton et al. (1979), Klock and McColley (1978) all noted a strong connection between soil moisture conditions and a soil's ability to bear a moving load due to the decrease in soil resistance along trails when soil moisture is increased. Weaver and Dale (1978), for example, noted that trails located on poorly drained soils are usually wider, deeper, and less uniform (i.e., greater roughness) than trails located on well drained sites.

4.3 Conclusions

Land managers need to assess the carrying capacities of their trail systems. Trail use in the last ten years has seen a dramatic increase in off-road bicycles. In many cases off-road bicyclists use the same trails as hikers, horseback riders and motorcyclists, so that this additional use compounds erosional concerns. The results of this study provide land managers with some new data summarizing the relative impacts of four different users on two existing trails in southwest Montana.

The four major findings of the study are: (1) the natural processes occurring on the two existing trails in this study demonstrate the complexity of topographic, soil, human, and geomorphic variables: (2) sediment yield from existing trails is detachment rather than transport-limited; (3) horses produce significantly larger quantities of sediment compared to hikers, off-road bicycles, and motorcycles; and (4) the largest and most frequent changes tend to occur on prewetted trails.

Future research needs to examine higher intensities of use (500 to 1000 passes) and increased rainfall intensities and soil saturation conditions (longer rainstorms). Higher levels of use and rainfall would increase the possibility of threshold values being attained. The development of models which simulate the attainment of erosion thresholds on existing trails could help land managers to assess the carrying capacities of their trail systems. However, it is still not clear how the results from small sample plots like those in this study can be extrapolated to other locations and/or to larger areas. Clearly, there is a need for this type of analysis prior to plans that reduce user conflicts and environmental impacts in national forests, state parks, and municipal recreation centers. The development and implementation of geographic information systems, models, and databases may help us to bridge this gap and therefore help in preserving the perceived intrinsic qualities of recreation areas.

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APPENDIX

Table 13. Emerald Lake trail slope, soil moisture, and water runoff data.

User	Prior condition[1]	Slope (%)	Soil moisture[2] 1 (%)	Soil moisture[3] 2 (%)	Water runoff[4] 1 (g)	Water runoff[5] 2 (g)
bike	D	1	27.8	27.8	-	810.1
bike	D	1	22.4	22.4	-	432.3
bike	D	1	50.2	50.2	-	762.7
bike	D	12	21.8	21.8	-	924.8
bike	D	12	32.8	32.8	-	147.7
bike	D	15	21.9	21.9	-	566.3
bike	P	1	16.7	39.9	377.4	354.4
bike	P	2	23.5	55.6	513.7	799.7
bike	P	2	20.8	24.2	249.2	788.9
bike	P	14	30.0	49.4	734.3	732.3
bike	P	13	26.6	29.6	465.6	851.3
bike	P	10	25.6	27.3	424.8	794.9
control	B	2	8.1	12.0	469.4	399.8
control	B	2	8.4	16.0	847.5	262.4
control	B	2	7.8	17.8	459.0	500.0
control	B	15	16.1	24.2	740.6	753.4
control	B	12	18.3	18.5	169.2	772.8
control	B	11	22.6	25.4	153.1	909.5
hiker	D	2	3.3	3.3	-	260.0
hiker	D	2	8.6	8.6	-	654.8
hiker	D	2	19.2	19.2	-	843.4
hiker	D	9	25.4	25.4	-	205.6
hiker	D	11	29.1	29.1	-	696.7
hiker	D	12	29.7	29.7	-	806.6
hiker	P	2	10.3	19.2	969.1	981.9
hiker	P	2	9.4	22.6	429.9	123.7
hiker	P	2	9.7	23.8	390.5	276.7
hiker	P	13	22.5	32.7	719.0	982.2
hiker	P	10	30.0	37.3	263.7	781.4
hiker	P	14	44.0	33.2	774.5	723.6
horse	D	2	32.5	32.5	-	788.5
horse	D	3	30.5	30.5	-	799.4
horse	D	3	30.0	30.0	-	487.3
horse	D	11	17.0	17.0	-	231.7
horse	D	13	23.2	23.2	-	588.1
horse	D	11	47.0	47.0	-	173.4
horse	P	5	21.4	30.1	57.8	307.3
horse	P	5	24.9	32.2	127.4	755.5
horse	P	6	20.1	40.0	985.1	156.8
horse	P	9	20.0	35.1	735.9	592.1
horse	P	9	24.0	37.5	155.0	201.3

Table 13. Emerald Lake trail slope, soil moisture, and water runoff data (continued).

User	Prior condition[1]	Slope (%)	Soil moisture[2] 1 (%)	Soil moisture[3] 2 (%)	Water runoff[4] 1 (g)	Water runoff[5] 2 (g)
horse	P	11	19.6	26.0	962.5	784.3
motor	D	3	20.1	20.1	-	318.9
motor	D	4	18.4	18.4	-	900.3
motor	D	3	20.2	20.2	-	187.6
motor	D	12	21.3	21.3	-	396.8
motor	D	13	18.0	18.0	-	799.6
motor	D	11	20.4	20.4	-	328.0
motor	P	3	20.6	35.5	560.0	531.2
motor	P	4	51.9	32.4	891.8	749.8
motor	P	3	50.3	59.6	100.8	774.4
motor	P	12	26.2	29.8	685.1	145.6
motor	P	14	32.4	34.1	781.0	649.9
motor	P	14	31.7	19.3	301.1	901.1

[1] Prior condition refers to state of sample plot prior to user treatments such that D, PW, and B indicate treatments applied to dry, prewetted, and both dry and prewetted situations, respectively.

[2] Soil moisture 1 refers to antecedent soil moisture.

[3] Soil moisture 2 refers to soil moisture prior to user treatments.

[4] Water runoff 1 refers to runoff collected prior to user treatments.

[5] Water runoff 2 refers to runoff collected after user treatments.

Table 14. Emerald Lake trail soil resistance and sediment yield data.

User	Prior condition	SR1[1]	SR2[2]	SR3[3] (kg/cm^2)	SR4[4]	SR5[5]	Sediment[6] yield 1 (g)	Sediment[7] yield 2 (g)
bike	D	37.02	-	44.72	39.94	22.54	-	50.9
bike	D	37.64	-	43.41	42.98	33.32	-	22.2
bike	D	39.55	-	41.18	39.67	28.39	-	27.0
bike	D	31.99	-	37.49	37.81	34.76	-	55.1
bike	D	34.59	-	35.59	39.94	36.55	-	78.0
bike	D	40.80	-	42.33	39.32	37.56	-	70.8
bike	P	42.75	31.83	30.05	31.38	25.62	40.7	38.8
bike	P	42.53	36.83	37.62	27.48	18.42	44.6	58.1
bike	P	44.33	37.88	39.03	36.92	27.50	20.8	33.0
bike	P	36.75	34.28	32.48	32.70	32.52	34.2	60.8
bike	P	39.28	35.48	33.72	36.53	34.51	40.8	54.2
bike	P	39.03	41.11	40.68	34.43	37.68	57.8	41.5
control	B	19.25	14.38	-	-	12.50	13.5	20.3
control	B	27.71	16.58	-	-	21.84	12.0	14.6
control	B	37.61	22.96	-	-	21.83	16.1	11.9
control	B	30.24	27.62	-	-	28.61	44.4	35.4
control	B	34.15	31.43	-	-	33.08	58.4	28.1
control	B	37.48	33.65	-	-	37.68	15.1	52.8
hiker	D	23.58	-	26.85	24.75	19.85	-	13.9
hiker	D	16.04	-	18.70	21.07	15.35	-	13.4
hiker	D	28.42	-	26.99	30.65	31.81	-	32.6
hiker	D	37.22	-	37.18	33.05	33.28	-	46.3
hiker	D	34.78	-	33.82	33.37	32.63	-	38.5
hiker	D	33.95	-	29.28	32.18	26.26	-	38.9
hiker	P	33.16	29.78	32.03	29.47	31.38	48.1	55.8
hiker	P	38.58	33.52	30.22	30.81	31.15	13.6	32.2
hiker	P	33.14	28.85	28.28	28.98	29.88	26.3	55.2
hiker	P	40.22	36.72	38.88	38.72	30.25	22.8	31.3
hiker	P	47.96	31.89	31.35	33.23	29.36	11.4	24.1
hiker	P	29.85	25.47	23.13	21.87	25.15	23.1	44.1
horse	D	33.55	-	34.48	34.38	24.65	-	53.0
horse	D	27.22	-	29.16	28.04	19.29	-	39.4
horse	D	31.54	-	28.52	28.55	20.34	-	65.1
horse	D	31.62	-	30.20	28.53	21.22	-	81.0
horse	D	29.18	-	26.65	33.72	24.48	-	84.0
horse	D	31.84	-	32.56	30.85	19.26	-	59.1
horse	P	27.94	24.27	22.58	23.22	17.79	24.0	61.5
horse	P	41.22	32.74	32.11	34.08	25.45	76.0	111.1
horse	P	29.25	23.50	20.72	20.72	23.30	66.5	79.5
horse	P	50.22	41.88	42.82	38.90	39.02	41.6	79.7
horse	P	42.12	30.48	29.55	30.02	26.09	81.0	83.1

Table 14. Emerald Lake trail soil resistance and sediment yield data (continued).

User	Prior condition	SR1[1]	SR2[2]	SR3[3] $(\mathrm{kg/cm^2})$	SR4[4]	SR5[5]	Sediment[6] yield 1 (g)	Sediment[7] yield 2 (g)
horse	P	39.19	30.68	27.44	29.53	28.76	106.3	117.5
motor	D	40.50	-	41.24	37.98	33.06	-	24.4
motor	D	41.62	-	41.31	42.55	35.63	-	27.1
motor	D	47.60	-	45.73	45.00	39.46	-	39.7
motor	D	38.72	-	43.08	43.50	36.58	-	27.8
motor	D	40.52	-	38.99	34.32	26.65	-	86.6
motor	D	40.41	-	36.35	34.38	20.20	-	14.8
motor	P	40.56	36.68	33.98	36.84	32.42	78.6	81.8
motor	P	44.02	40.99	35.23	37.18	38.23	24.3	84.0
motor	P	34.76	31.48	29.33	29.17	28.27	10.6	85.3
motor	P	42.90	34.57	33.98	32.90	28.44	83.4	112.6
motor	P	34.62	29.35	27.06	28.83	26.35	45.5	114.8
motor	P	34.52	27.61	23.04	26.40	16.45	39.2	51.3

1 SR1 refers antecedent soil resistance.
2 SR2 represents to soil resistance prior to user treatments.
3 SR3 represents soil resistance after 50 passes of a user.
4 SR4 represents soil resistance after 100 passes of a user.
5 SR5 represents soil resistance after final rainfall.
6 Sediment yield 1 refers to sediment collected prior to user treatment.
7 Sediment yield 2 refers to sediment collected after user treatment.

Table 15. Emerald Lake trail roughness data.

User	Prior condition	TR1[1] (mm)	TR2[2] (mm)	TR3[3] (mm)	TR4[4] (mm)	TR5[5] (mm)
bike	D	202.31	-	202.63	203.62	203.12
bike	D	201.17	-	200.89	201.18	201.11
bike	D	199.52	-	198.77	197.60	198.40
bike	D	205.52	-	204.20	204.97	204.85
bike	D	208.80	-	209.80	209.74	208.55
bike	D	205.60	-	204.88	206.51	204.43
bike	P	200.62	200.68	201.00	199.98	200.42
bike	P	196.17	195.77	195.78	196.43	196.58
bike	P	202.06	201.35	201.62	198.54	198.68
bike	P	200.29	199.94	199.77	200.03	200.12
bike	P	204.15	204.42	204.32	203.74	203.85
bike	P	200.05	199.88	198.11	197.60	197.66
control	B	195.72	195.26	-	-	195.80
control	B	195.46	193.91	-	-	193.92
control	B	198.97	196.75	-	-	195.22
control	B	201.92	202.22	-	-	201.68
control	B	206.86	203.58	-	-	203.97
control	B	203.48	202.94	-	-	202.88
hiker	D	192.45	-	190.92	191.34	189.17
hiker	D	200.89	-	201.52	201.98	200.15
hiker	D	206.37	-	206.29	204.40	204.66
hiker	D	212.57	-	213.74	212.86	212.45
hiker	D	216.43	-	214.63	216.26	215.12
hiker	D	213.45	-	213.29	212.89	213.63
hiker	P	211.28	211.89	212.43	209.72	210.12
hiker	P	199.35	199.20	199.89	199.14	199.12
hiker	P	208.54	208.57	209.23	208.17	208.43
hiker	P	199.69	199.52	199.25	198.72	198.62
hiker	P	199.34	198.68	199.17	199.17	198.17
hiker	P	195.37	194.94	195.57	194.49	194.98
horse	D	198.25	-	198.69	198.88	198.37
horse	D	203.95	-	203.29	205.45	203.11
horse	D	201.57	-	203.42	203.66	201.65
horse	D	200.97	-	200.57	201.02	200.80
horse	D	214.74	-	215.26	212.85	213.45
horse	D	197.51	-	198.09	197.03	197.80
horse	P	204.12	205.42	205.14	205.28	206.48
horse	P	207.48	208.26	208.12	208.52	208.23
horse	P	206.72	207.22	207.15	205.98	207.35
horse	P	205.40	205.05	205.75	205.58	206.17
horse	P	206.83	206.77	207.40	206.12	206.65
horse	P	211.32	211.52	212.54	211.14	210.75
motor	D	200.23	-	200.32	199.92	199.63
motor	D	209.09	-	209.09	209.48	209.22

Table 15. Emerald Lake trail roughness data (continued).

User	Prior condition	TR1[1] (mm)	TR2[2] (mm)	TR3[3] (mm)	TR4[4] (mm)	TR5[5] (mm)
motor	D	199.26	-	199.34	198.35	198.74
motor	D	205.60	-	204.78	204.68	205.06
motor	D	210.49	-	200.88	210.57	201.02
motor	D	204.42	-	204.25	203.71	204.00
motor	P	201.66	201.48	202.66	204.12	203.55
motor	P	207.52	206.85	208.14	207.22	207.52
motor	P	201.17	200.51	199.14	199.82	200.09
motor	P	202.02	201.85	202.98	202.00	202.38
motor	P	216.93	217.34	217.66	218.38	217.26
motor	P	206.12	205.94	205.18	205.35	205.85

[1] TR1 refers to antecedent trail roughness.
[2] TR2 represents trail roughness prior to user treatment.
[3] TR3 represents trail roughness after 50 passes of a user.
[4] TR4 represents trail roughness after 100 passes of a user.
[5] TR5 represents trail roughness after the final rainfall.

Table 16. New World Gulch trail slope, soil moisture, and water runoff data.

User	Prior condition[1]	Slope (%)	Soil moisture[2] 1 (%)	Soil moisture[3] 2 (%)	Water runoff[4] 1 (g)	Water runoff[5] 2 (g)
bike	D	4	18.0	18.0	-	228.4
bike	D	4	15.8	15.8	-	203.4
bike	D	4	16.9	16.9	-	765.1
bike	D	13	20.6	20.6	-	994.9
bike	D	15	22.3	22.3	-	279.6
bike	D	19	27.3	27.3	-	753.1
bike	P	4	8.9	25.3	121.6	590.0
bike	P	5	9.5	29.8	607.2	249.3
bike	P	5	8.1	24.5	702.1	781.9
bike	P	16	7.9	27.6	295.9	849.1
bike	P	14	18.0	25.8	134.2	581.1
bike	P	11	16.9	20.3	99.5	722.8
control	B	3	6.7	23.9	521.2	769.7
control	B	3	6.9	24.6	618.9	829.0
control	B	4	6.6	27.5	271.2	823.2
control	B	15	22.8	32.6	52.1	814.7
control	B	17	23.8	41.3	364.8	723.2
control	B	21	23.6	48.3	371.1	372.1
hiker	D	4	12.0	12.0	-	330.0
hiker	D	4	10.1	10.1	-	751.8
hiker	D	4	11.2	11.2	-	761.2
hiker	D	13	28.7	28.7	-	254.4
hiker	D	13	24.8	24.8	-	301.8
hiker	D	14	25.1	25.1	-	254.1
hiker	P	3	8.8	26.5	616.4	650.9
hiker	P	2	17.9	25.1	127.2	926.7
hiker	P	2	20.6	27.6	286.3	741.2
hiker	P	13	13.7	27.9	760.7	457.9
hiker	P	13	12.1	26.3	456.9	524.0
hiker	P	13	6.0	29.5	469.2	854.4
horse	D	5	15.0	15.0	-	85.5
horse	D	5	14.5	14.5	-	203.2
horse	D	5	15.9	15.9	-	353.7
horse	D	15	17.1	17.1	-	369.4
horse	D	15	13.7	13.7	-	288.4
horse	D	11	15.3	15.3	-	320.4
horse	P	5	7.8	29.8	709.4	217.6
horse	P	5	12.1	27.2	57.2	953.2
horse	P	5	15.6	18.6	685.4	303.1
horse	P	12	6.6	23.7	649.5	972.4
horse	P	13	29.7	37.6	431.4	111.9

Table 16. New World Gulch trail slope, soil moisture, and water runoff data (continued).

User	Prior condition[1]	Slope (%)	Soil moisture[2] 1 (%)	Soil moisture[3] 2 (%)	Water runoff[4] 1 (g)	Water runoff[5] 2 (g)
horse	P	17	27.6	34.0	896.2	715.3
motor	D	5	14.4	14.4	-	941.1
motor	D	5	15.2	15.2	-	815.3
motor	D	6	16.9	16.9	-	506.5
motor	D	9	16.3	16.3	-	408.5
motor	D	14	19.5	19.5	-	901.1
motor	D	19	19.5	19.5	-	358.6
motor	P	4	11.8	24.7	916.8	666.6
motor	P	3	14.4	26.3	931.6	649.5
motor	P	5	14.8	29.6	226.8	631.5
motor	P	14	19.6	35.6	671.3	497.4
motor	P	19	24.9	31.6	766.2	493.6
motor	P	21	21.2	41.6	579.8	827.9

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[1] Prior condition refers to states of sample plot prior to user treatments. D, PW and B indicate treatments were applied to dry, prewetted, and both dry and prewetted situations, respectively.

[2] Soil moisture 1 refers to initial antecedent soil moisture.

[3] Soil moisture 2 refers to soil moisture prior to user treatments.

[4] Water runoff 1 refers to collected runoff prior to user treatments.

[5] Water runoff 2 refers to collected runoff after user treatments.

Table 17. New World Gulch trail soil resistance and sediment yield data.

User	Prior condition	SR1[1]	SR2[2]	SR3[3] (kg/cm^2)	SR4[4]	SR5[5]	Sediment[6] yield 1 (g)	Sediment[7] yield 2 (g)
bike	D	49.12	-	43.50	43.27	40.84	-	56.8
bike	D	44.37	-	43.44	46.01	36.59	-	58.5
bike	D	40.88	-	42.75	42.41	30.67	-	57.1
bike	D	40.89	-	39.10	38.29	33.62	-	37.3
bike	D	38.61	-	36.05	37.32	30.34	-	50.4
bike	D	33.54	-	29.12	30.71	30.48	-	56.3
bike	P	54.32	43.44	43.06	41.35	36.65	69.3	78.6
bike	P	48.97	31.25	34.45	39.61	30.15	138.6	86.3
bike	P	49.34	35.62	31.76	36.12	37.51	94.3	98.8
bike	P	40.12	24.36	20.73	24.38	18.97	161.2	96.6
bike	P	31.25	27.95	26.65	30.65	26.59	48.2	60.4
bike	P	35.97	31.66	31.57	32.59	27.99	55.2	62.4
control	B	56.61	43.93	-	-	35.74	49.9	69.2
control	B	57.25	50.95	-	-	38.21	87.7	117.7
control	B	56.45	43.77	-	-	31.25	111.1	85.3
control	B	34.19	29.72	-	-	28.47	48.1	102.1
control	B	34.50	32.72	-	-	23.98	137.8	84.4
control	B	32.52	22.79	-	-	24.39	58.8	138.2
hiker	D	52.42	-	46.64	47.92	44.62	-	84.4
hiker	D	52.09	-	47.70	49.18	45.47	-	90.7
hiker	D	51.63	-	47.19	51.18	48.25	-	92.4
hiker	D	26.55	-	27.41	26.96	24.09	-	81.0
hiker	D	27.98	-	25.61	29.97	23.84	-	87.4
hiker	D	25.56	-	26.92	27.83	25.27	-	106.8
hiker	P	48.42	42.28	41.48	37.71	36.38	75.2	84.9
hiker	P	42.35	31.93	31.66	30.20	27.95	49.7	95.9
hiker	P	34.60	26.02	26.22	24.45	24.98	73.7	93.7
hiker	P	49.04	41.63	36.95	36.25	34.65	81.4	95.3
hiker	P	54.30	43.69	41.23	37.55	38.98	47.0	106.5
hiker	P	36.01	17.64	21.15	21.82	16.42	66.6	66.7
horse	D	52.22	-	46.14	49.15	28.31	-	70.4
horse	D	49.90	-	44.72	49.60	28.89	-	81.9
horse	D	50.39	-	49.61	47.70	31.10	-	126.3
horse	D	47.54	-	40.35	44.92	33.53	-	64.2
horse	D	50.02	-	45.34	48.72	33.15	-	132.8
horse	D	46.03	-	46.59	45.77	38.46	-	115.2
horse	P	56.78	41.19	42.84	46.18	35.94	37.1	73.5
horse	P	49.10	41.08	32.40	35.72	36.90	47.9	178.5
horse	P	45.27	35.30	35.12	35.52	34.26	115.5	63.2
horse	P	46.59	32.74	33.18	33.45	25.92	63.7	97.5
horse	P	28.70	20.39	24.50	24.75	23.95	42.6	115.1

Table 17. New World Gulch trail soil resistance and sediment yield data (continued).

User	Prior condition	SR1[1]	SR2[2]	SR3[3] (kg/cm^2)	SR4[4]	SR5[5]	Sediment[6] yield 1 (g)	Sediment[7] yield 2 (g)
horse	P	24.66	19.98	22.25	20.39	19.92	85.9	137.6
motor	D	38.47	-	37.13	34.99	30.55	-	41.6
motor	D	38.42	-	37.25	33.95	29.42	-	61.3
motor	D	35.74	-	36.05	35.24	28.72	-	33.1
motor	D	34.78	-	30.22	31.47	22.44	-	66.5
motor	D	29.95	-	30.80	27.32	22.55	-	41.2
motor	D	28.90	-	28.72	28.38	26.16	-	102.8
motor	P	47.20	35.90	32.82	30.98	31.02	37.4	67.4
motor	P	45.77	35.92	29.92	33.12	32.68	96.9	74.0
motor	P	42.26	28.38	28.53	27.70	25.24	60.8	92.4
motor	P	45.05	26.01	27.30	27.57	25.96	72.8	90.2
motor	P	31.12	28.46	21.50	22.68	10.35	156.2	85.9
motor	P	32.13	22.25	26.29	26.75	25.05	153.0	141.8

1 SR1 refers antecedent soil resistance.
2 SR2 represents to soil resistance prior to user treatments.
3 SR3 represents soil resistance after 50 passes of a user.
4 SR4 represents soil resistance after 100 passes of a user.
5 SR5 represents soil resistance after final rainfall.
6 Sediment yield 1 refers to sediment collected prior to user treatment.
7 Sediment yield 2 refers to sediment collected after user treatment.

Table 18. New World Gulch trail roughness data.

User	Prior condition	TR1[1] (mm)	TR2[2] (mm)	TR3[3] (mm)	TR4[4] (mm)	TR5[5] (mm)
bike	D	197.00	-	197.62	197.85	198.78
bike	D	195.97	-	196.60	197.09	198.22
bike	D	197.00	-	196.22	196.86	196.52
bike	D	237.69	-	237.05	237.94	238.83
bike	D	229.12	-	229.28	229.05	230.35
bike	D	247.48	-	253.91	247.83	246.78
bike	P	201.40	203.12	203.23	202.17	202.28
bike	P	204.78	206.22	206.82	206.72	207.20
bike	P	208.74	210.77	211.75	210.48	210.80
bike	P	242.38	242.09	238.00	242.62	243.06
bike	P	243.29	244.22	243.66	242.55	243.28
bike	P	227.97	228.18	228.55	228.00	228.09
control	B	206.92	207.65	-	-	206.22
control	B	215.11	217.08	-	-	216.22
control	B	217.58	219.11	-	-	218.98
control	B	220.74	219.89	-	-	220.22
control	B	213.58	214.12	-	-	214.20
control	B	218.46	219.02	-	-	219.43
hiker	D	205.48	-	205.85	206.54	207.28
hiker	D	204.05	-	203.26	202.62	202.22
hiker	D	202.32	-	202.08	201.58	202.14
hiker	D	236.45	-	235.86	230.06	237.83
hiker	D	236.60	-	239.31	237.26	235.57
hiker	D	227.02	-	227.08	226.20	226.57
hiker	P	211.20	212.95	212.49	210.12	210.35
hiker	P	195.40	195.72	196.15	196.29	196.55
hiker	P	197.14	197.48	197.92	197.68	198.43
hiker	P	201.38	201.82	202.38	201.66	201.69
hiker	P	197.75	198.08	198.29	198.08	198.51
hiker	P	237.65	236.26	235.55	235.43	234.65
horse	D	196.80	-	196.20	196.40	198.29
horse	D	197.75	-	200.95	196.35	196.86
horse	D	199.29	-	199.03	200.12	200.34
horse	D	243.52	-	243.95	244.00	246.52
horse	D	238.11	-	239.94	239.86	240.68
horse	D	223.62	-	223.05	222.54	223.68
horse	P	210.83	209.77	206.66	203.57	204.42
horse	P	218.85	220.42	218.83	218.68	219.66
horse	P	206.00	206.49	205.60	206.35	206.46
horse	P	200.08	200.34	199.98	200.49	210.43
horse	P	234.95	236.09	232.62	232.00	235.55
horse	P	218.17	217.82	216.00	213.25	214.37
motor	D	210.51	-	211.82	211.43	211.98

Table 18. New World Gulch trail roughness data (continued).

User	Prior condition	TR1[1] (mm)	TR2[2] (mm)	TR3[3] (mm)	TR4[4] (mm)	TR5[5] (mm)
motor	D	211.14	-	210.74	211.15	210.80
motor	D	205.35	-	206.28	205.62	205.15
motor	D	208.26	-	209.18	208.92	208.00
motor	D	208.98	-	209.48	213.57	207.92
motor	D	204.42	-	202.40	200.85	202.20
motor	P	215.40	216.45	217.02	215.94	216.94
motor	P	205.25	205.65	206.05	205.98	206.35
motor	P	194.71	194.66	195.25	195.12	195.22
motor	P	233.88	234.80	231.09	232.88	233.20
motor	P	214.49	215.72	215.77	216.14	216.08
motor	P	208.80	209.43	209.60	208.45	208.72

[1] TR1 refers to antecedent trail roughness.
[2] TR2 represents trail roughness prior to user treatment.
[3] TR3 represents trail roughness after 50 passes of a user.
[4] TR4 represents trail roughness after 100 passes of a user.
[5] TR5 represents trail roughness after the final rainfall.